Supply Chain Disruption Management: how to cope with the semiconductor shortage problem in the automotive industry

Case Study of Volkswagen Autoeuropa

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

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Abstract

Nowadays, the automotive industry has been facing a major supply chain disruption (SCD) caused by semiconductor shortages. As a result, automotive SCs are exposed to several supply chain risks (SCRs) that can negatively impact companies' operations and jeopardize supply chain resilience (SCRES). Volkswagen Autoeuropa (VW AE), an automotive plant located in Portugal and belonging to the Volkswagen Group, is no exception and has been also suffering with the semiconductor crisis problem.

This work was developed in partnership with VW AE and has two main objectives: 1) perform a thorough study of VW AE´s semiconductor SC, in order to cope with the problem of semiconductor shortages; and 2) contribute to the literature with the development of a real case study in an automotive company that addresses the referred problem and studies the concepts of SCD, SCRM and SCRES.

After performing a comprehensive literature review based on SCD, SCRM and SCRES, it was chosen the supply chain risk management (SCRM) process as the main methodology to study the SCRs that the semiconductor SC of VW AE has been facing. This holistic process permitted: 1) identifying the two most relevant risks (supply failure and production failure); 2) assessing the overall risk score of occurring a production failure; 3) analysing the mitigation measures already implemented by VW AE; 4) proposing new mitigation measures to decrease the probability of occurring a production failure and suggesting measures to increase SCRES in VW AE´s SC; and 5) raising awareness of the importance of SCRM process to deal with SCDs.

Keywords: Supply Chain Disruption; Supply Chain Risk Management; Supply Chain Resilience; Automotive Industry; Semiconductor Industry.

Resumo

Atualmente, a indústria automóvel tem enfrentado uma enorme disrupção da cadeia de abastecimento causada pela escassez de semicondutores. Assim, as cadeias de abastecimento automóveis estão expostas a vários riscos que podem impactar negativamente as operações das empresas e comprometer a resiliência das cadeias. A Volkswagen Autoeuropa (VW AE), fábrica automóvel localizada em Portugal e pertencente ao Grupo Volkswagen, não é exceção e tem também sofrido com o problema da crise dos semicondutores.

Este trabalho foi desenvolvido em parceria com a VW AE e tem dois objetivos principais: 1) realizar um estudo aprofundado da cadeia de abastecimento de semicondutores da VW AE, de forma a lidar com o problema de falta de semicondutores; e 2) contribuir para a literatura com o desenvolvimento de um caso de estudo real sobre uma empresa automóvel, que aborde o referido problema e estude os conceitos de disrupção, gestão de risco e resiliência da cadeia de abastecimento.

Após realizar uma exaustiva revisão de literatura baseada na disrupção, gestão de risco e resiliência da cadeia de abastecimento, foi escolhido o processo de gestão de risco da cadeia de abastecimento como principal metodologia para estudar os riscos que a cadeia de abastecimento de semiconductores da VW AE tem vindo a enfrentar. Este processo holístico permitiu: 1) identificar os dois riscos mais relevantes (falha de abastecimento e falha de produção); 2) avaliar a pontuação geral do risco de ocorrer uma falha de produção; 3) analisar as medidas de mitigação já implementadas pela VW AE; 4) propor novas medidas de mitigação para diminuir a probabilidade de ocorrência de uma falha de produção e sugerir medidas para aumentar a resiliência da cadeia de abastecimento de semicondutores da VW AE; e 5) consciencializar sobre a importância do processo de gestão de risco na cadeia de abastecimento para lidar com disrupções.

Palavras-chave: disrupção da cadeia de abastecimento; gestão de risco da cadeia de abastecimento; resiliência da cadeia de abastecimento; indústria automóvel; indústria de semiconductores.

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Acronyms

AHP	Analytical Hierarchy Process
BN	Bayesian Network
BNK	*BeschaffungNebenKosten*
CPT	Conditional Probability Table
EDI	Electronic Data Interchange
EU	European Union
FMEA	Failure Mode and Effect Analysis
GDP	Gross Domestic Product
GVA	Gross Value Added
IDM	Integrated Device Manufacturer
JIS	Just in Sequence
JIT	Just in Time
KPI	Key Performance Indicator
MIB	Modular Info-entertainment Toolkit
OEM	Original Equipment Manufacturer
PP	Percentual Points
R&D	Research and Development
RM	Risk Management
SC	Supply Chain
SCD	Supply Chain Disruption
SCM	Supply Chain Management
SCR	Supply Chain Risk
SCRA	Supply Chain Risk Assessment
SCRES	Supply Chain Resilience
SCRI	Supply Chain Risk Identification
SCRM	Supply Chain Risk Management
SCRT	Supply Chain Risk Treatment
TSMC	Taiwan Semiconductor Manufacturing Company
US	United States
VW	Volkswagen
VW AE	Volkswagen Autoeuropa
3PL	Third-Party Logistics

1 Introduction

The purpose of the current chapter is to provide an adequate context of the problem that is going to be addressed during this master dissertation, as well as define the purpose, main goals and structure of the thesis. In section 1.1 the problem is contextualized and a motivation for the work is done. In section 1.2 the dissertation’s purpose and intermediate goals are pointed out and in section 1.3 the structure of the document is presented.

1.1 Problem contextualization and motivation

Nowadays, supply chains (SCs) are becoming more and more complex, interdependent and exposed to supply chain risks (SCRs) (Shekarian & Parast, 2021), which enhances the occurrence of supply chain disruptions (SCD) that negatively impact companies’ operations (Katsaliaki et al., 2021). The automotive sector is no exception and has been facing a major SCD due to semiconductor shortages, induced by the COVID-19 pandemic (Ramani et al., 2022). This worldwide semiconductor crisis has been causing a massive ripple effect that has affected automotive companies. Volkswagen (VW) and Toyota have closed production facilities in China, while Fiat Chrysler has suspended production lines in Mexico and Canada, and Nissan and Daimler reduced their automotive production in Japan and Europe (Wu et al., 2021). According to the consulting firm AlixPartners, the ongoing semiconductor chip crisis might have generated a total loss in revenues for the global automotive industry equal to 110 billion dollars, in 2021 (Wayland, 2021). As result, due to these chip shortages, automakers are closely collaborating with semiconductor suppliers, signing deals to secure supplies in the future, reducing the risk of supply failures, as did BMW with Inova Semiconductors and Global Foundries or Stellantis with Foxconn (Ramani et al., 2022). Moreover, knowing that semiconductors play a significant role in modern society, not only for the automotive industry, but also for technological companies (Mckinsey, 2022), governments and other international institutions are fostering investments to increase the production of semiconductors. In February 2022, the European Commission presented a proposal for a European Chips Act to reinforce the whole European chips value chain, based on three pillars: 1) bolster large-scale technological capacity building and innovation in the European Union (EU) chips ecosystem; 2) improve the EU's security of supply, by attracting investment and enhancing production capacities in the EU; and 3) set up a monitoring and crisis response mechanism (Ragonnaud, 2022). In July 2022, the United States (US) congress also approved a 50-billion-dollar plan proposed by the Biden administration to build up the American semiconductor industry, being considered the most significant investment in industry policy that the US has made in the last 50 years (Swanson, 2022).

In this way, considering the negative impacts that the semiconductor disruption has been producing in the automotive sector, it is critical to study in depth the semiconductor SC of the automotive industry, in order to be aware of the main SCRs that led to the current SCD and to try to mitigate them, fostering supply chain resilience (SCRES). This can be done through a supply chain risk management (SCRM) process that permits identifying, assessing, treating and monitoring SCRs.

The case study of this master thesis was developed in Volkswagen Autoeuropa (VW AE), which is the biggest vehicle manufacturer in Portugal (Fábio Carvalho da Silva, 2021). VW AE, like the majority of automotive plants, has been severely affected by the semiconductor disruption induced by the COVID-19 pandemic, being obliged to stop its production lines several times in 2021 due to semiconductor shortages. These production halts led to backorders, a high increase in customer lead time and a decrease in profits. Although some reactive measures have been already applied, the problem of chip shortages persists and a comprehensive study that analyses the problem urges to be developed, focusing on the whole SCRM process. It is because of this need to study the VW AE´s semiconductor SC that this work emerges.

1.2 Purpose and intermediate goals

This work aims to perform a thorough study of VW AE´s semiconductor SC, in order to cope with the problem of semiconductor shortage that is affecting all company´s operations. Simultaneously, it also intends to contribute to the literature with the development of a real case study in an automotive company that addresses the referred problem and studies the concepts of SCD, SCRM and SCRES. To this, the current dissertation targets the following intermediate goals:

- Study the automotive and semiconductor industries, to understand their main characteristics;
- Identify the main risks and threats that are affecting the automotive and semiconductor industries;
- Perform a comprehensive literature review focused on SCD, SCRM and SCRES in order to understand these concepts and identify the main research topics and gaps;
- Develop a holistic methodology that allows to:
    - Identify the main SCRs that VW AE has been facing during the semiconductor shortage;
    - Assess the impact and probability of occurrence of the main SCRs identified;
    - Evaluate the measures already implemented by VW AE and propose new mitigation measures to treat the SCRs and foster SCRES;
- Analyse and critically discuss the assumptions made and the results obtained.

1.3 Master thesis structure

This master thesis will be divided into seven distinct chapters, each of them organized as follows:

1) **Introduction** – The first chapter explains the problem contextualization and motivation, and points out the purpose of the work and the intermediate goals that need to be accomplished. Besides, it is also presented the structure of the document.
2) **Automotive and Semiconductor Industries** – In the second chapter, a thorough study of the automotive and semiconductor industries is made, in order to understand the semiconductor disruption problem that the automotive industry is facing. The main characteristics of both industries are presented, and an especial focus is placed on the threats and risks existent at their interface.
3) **Case Study Volkswagen Autoeuropa** – In the third chapter, the case study is presented. Firstly, a brief characterization of the VW group and VW AE is performed. Then, an analysis of VW AE´s SC is carried out in order to understand the main categories of suppliers and to establish a boundary for the study. The chapter ends with the analysis of the semiconductor SC and the impact that the semiconductor disruption has had on VW AE.
4) **Literature Review** – The fourth chapter provides a comprehensive literature review with the main objective of investigating the concepts associated with the problem previously stated, presenting the major research topics. In this way, the most relevant ideas related to SCD management are going to be studied, in order to examine which models are suitable to analyse the semiconductor disruption in the automotive industry. An especial focus is dedicated to SCD, SCRM and SCRES.
5) **Methodology and Discussion** – The fifth chapter contains the methodology that is going to be applied to study the semiconductor disruption problem that is affecting the automotive industry: the SCRM process. This methodology is composed of four stages: supply chain risk identification (SCRI); supply chain risk assessment (SCRA); supply chain risk treatment (SCRT) and supply chain risk monitoring. Each stage of the SCRM process is going to be discussed in detail.
6) **Critical Analysis** – The sixth chapter has the goal of critically analysing the methodology used in this study, this is, the SCRM process, namely some topics of the SCRA and SCRT stages. In this way, sensitivity and scenario analyses are going to be performed.
7) **Conclusions** – The closing chapter of this master thesis focuses on presenting the final conclusions of the work and pointing out the relevant aspects and research avenues to be considered in the future.

2 Automotive and semiconductor industries

This chapter has the objective of presenting the main characteristics of the automotive and semiconductor industries, which are critical to understand the problem stated before and the work that is going to be developed hereafter. Firstly, the automotive industry is introduced. A brief overview of the industry is made and a characterization of how works its production system and its SC is pointed out. A short characterization of the automotive industry in Portugal is also carried out. Then, the semiconductor industry is introduced. The characteristics and the impact of the industry are presented, as well as the market and main players. Moreover, the threats and risks of the semiconductor industry are exposed. Finally, the importance of semiconductors in the automotive industry is explained and the risks and paradigmatic disruptions in the interface between the automotive and semiconductor industries are also addressed.

2.1 Automotive industry

2.1.1 Global overview and impact

The automotive industry is currently spread worldwide and has changed people´s lives and leveraged the economy of several countries. This industry provides a wide range of benefits for economies because it not only creates economic development, through the attraction of foreign direct investments and the increase of Gross Domestic Product (GDP), but also fosters people development, through the creation of jobs (McKinsey & Company, 2019). Besides, it also massively contributes to research and technology, being considered the largest private investor in research and development (R&D) and one of the most innovative sectors in the EU (European Commission, 2022). According to the European Commission (2022), the turnover generated by the automotive industry represents over 7 % of the EU GDP. In social terms, the sector employs around 13.8 million people in the EU, representing 6.1% of total EU employment and being transportation, manufacturing, sales and maintenance the more intensive working areas. In terms of production, in the last decade, a change has occurred in the ranking of worldwide car manufacturing countries. Contrary to the beginning of the century, when North America, Japan and Western Europe were the major producers, today, emerging countries like China and India have become important players (Mathilde Carlier, 2021). As Figure A. 1 (appendix A) illustrates, the biggest producer of passenger cars in 2021 was, by far, China, followed by Japan, India, South Korea and Germany (Statista, 2022a).

2.1.2 Just in Time (JIT) and Just in Sequence (JIS) production systems

Taking into account that the core business of any car manufacturer is the production of vehicles, the production system adopted by companies plays a critical role in their strategy. Nowadays, the majority of car manufacturers apply the Just in Time (JIT) production system, originally implemented by Toyota (Sugimori et al., 1977). JIT is a production and inventory control system that guarantees that the materials are delivered by the supplier in the manufacturing plant, in the right quantities, at the right time and in the exact location (Sugimori et al., 1977). The main objective of this system is to prevent the waste generated by excessive stock and the overproduction of goods. In this way, when the JIT system is applied, the levels of inventory are very low and the stock has a high rotation, which contributes to decrease the costs associated not only with the storage, but also with the handling of materials and the feeding of assembly lines (Graf, 2006). Overall, JIT fosters efficiency since it eliminates activities that do not add value and reduces costs (Graf, 2006). This JIT system is triggered by the customer orders, working as a pull system of production, because it is the customer order that determines the production of the car (Yavuz & Aķali, 2007). In this way, the automotive industry follows a make-to-order policy, instead of make-to-stock, as cars are produced only as needed and to meet actual customer demand (Yavuz & Aķali, 2007). More recently, with the increase in innovation and client´s requirements in the customization of cars, a new concept, called Just in Sequence (JIS), has emerged from JIT (Wagner & Silveira-Camargos, 2012). Thus, the JIS system satisfies not only the JIT principles, this is, the product arrives in the right quantities, at the right time and at the right location, but also guarantees that the sequence of the supplies is aligned with the production sequence of the assembly line (Werner et al., 2003). Now, the task of sequencing the products, that in JIT is done in the manufacturing plant, is left to suppliers, which enhances their responsibilities. The cost of getting the parts in the right sequence is now transferred to the supplier. Therefore, JIS is much more demanding than JIT and constitutes an extra challenge to suppliers (J.-H. Thun & Marble, 2007). Nowadays car manufacturers, also called Original Equipment Manufacturer (OEM), use to combine JIT and JIS in their facilities (Cedillo-Campos et al., 2017).

However, in spite of having several advantages, JIT and JIS also present some implications and drawbacks. Firstly, to assure that these systems work properly, it is indispensable that an excellent and solid relationship exists between OEMs and their suppliers (Wagner & Silveira-Camargos, 2012). As the JIT and JIS are demanding systems in terms of functioning, usually only one first-tier supplier exists for each type of material, this is, usually OEMs have single-source supply policies (Fourcade & Midler, 2005). This promotes cost savings and allows OEMs to maintain a close relationship with suppliers. Nevertheless, building this relationship might be difficult and takes time. Besides, although it has the advantage of cost savings, single sourcing is very risky because, when an accident happens at the suppliers' facility or another external factor exists that limits the flow of materials, SCD can occur (Wagner & Silveira-Camargos, 2012). If this disruption persists for a long period, it could cause catastrophic consequences in OEMs operations. Ultimately, it could induce the stoppage of OEMs' production lines, which limits the capacity to satisfy the demand and could even jeopardize the profitability and damage the reputation of the company. Indeed, as the inventory levels associated with JIT and JIS systems are very low, even a small disturbance can have a considerable impact on OEM's operations (Wagner & Silveira-Camargos, 2012). Furthermore, another limitation induced by JIT and JIS systems is the low capacity to react to problems since, if an error in supplies' schedule occurs, a high risk of not delivering the supplies on time to the OEM exists (Dinsdale & Bennett, 2015).

Overall, JIT and JIS can represent a huge opportunity for the company's success, by reducing stock and handling costs and increasing operational efficiency. However, these two systems have a deep impact on all SC of an automotive company, not only in its production and logistics, but also in the operation of their upstream suppliers. As a result, it is indispensable that not only all company areas work in a coordinated way, but also that the other echelons of the SC have close relationships (J.-H. Thun & Marble, 2007). Moreover, it is of the utmost importance that the OEM does not ignore the risks associated with JIT and JIS, building countermeasures like contingency plans to avoid disturbances and mitigate the impact of a possible disruption if it occurs (Wagner & Silveira-Camargos, 2011).

2.1.3 Automotive SC

As was previously mentioned, the automotive industry is a driver of economic growth, being responsible for sustaining a diverse range of businesses, upstream and downstream of the main business. The core of the automotive industry is composed of OEMs, responsible for vehicles production, and component manufacturers (Klink et al., 2014). Upstream in the SC, are located all the suppliers, such as metals and electronics suppliers, while downstream is also located a wide set of segments, such as car dealers and rentals, as is represented in Figure 1 (Klink et al., 2014). Besides, there are also adjacent industries, like finance and legal, which work as a support along with the SC (Klink et al., 2014).

The automotive SC is formed by several interconnected and interdependent echelons. Upstream of the OEM, the SC is constituted by numerous layers or tiers, whose main objective is, directly or indirectly, to supply the manufacturer with the components or subsystems needed for the final assembly. In this way, the first-tier suppliers are in the majority of the cases JIT and JIS suppliers, responsible for delivering the subassemblies, such as interior or power train assemblies, in the right time, quantity and location, and exact sequence required for the final assembly (Fourcade & Midler, 2005). Due to these JIT and JIS policies, these suppliers are generally located nearby the OEM's factory in order to accomplish the demanding lead time and the short delivery time windows (Fourcade & Midler, 2005). More upstream are located the second-tier suppliers, in charge of manufacturing and delivering some parts and components used by first-tier suppliers in their subassemblies. This sequence can be observed in Figure 2 (Chandra & Kamrani, 2004). Nevertheless, it is important to underline that the figure is simplified because only three tiers of suppliers are represented (first tier, second tier and raw materials suppliers). Automotive SCs can be formed by more than 3 tiers, which increases even more the complexity (Volkswagen Autoeuropa, 2021). Downstream of the OEMs, other echelons exist, such as car dealers and the final consumers (Chandra & Kamrani, 2004). Once again, Figure 2 is a simplified scheme because, in general, cars are transported to a logistics hub (distribution centre) before going to car dealers. It is this logistic hub that generally is responsible for doing the final distribution to the dealers.

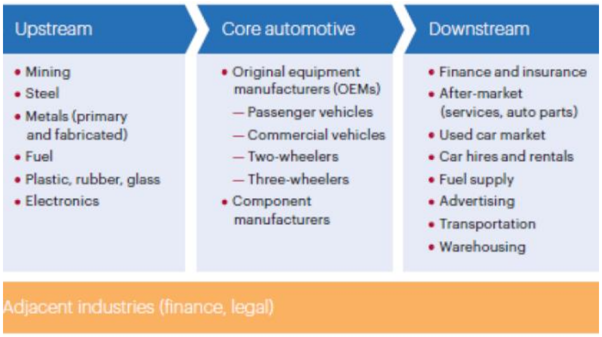

Figure 1 - Automotive industry and associated businesses. Source: Extracted from (Klink et al., 2014)

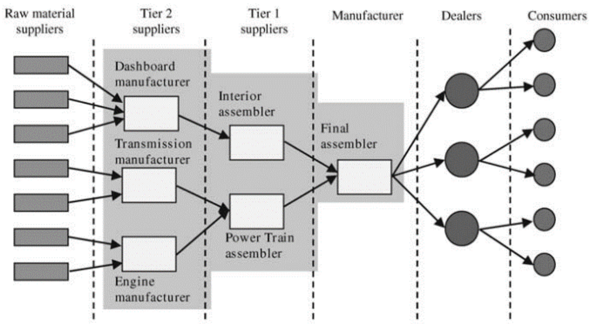

Figure 2 - General scheme of an Automotive SC. Source: Extracted from (Chandra & Kamrani, 2004)

2.1.4 Automotive industry in Portugal

The automotive industry plays a critical role in the Portuguese economy. In 2020, the automotive sector encompassed 752 companies and more than 43,000 employees, despite the decrease suffered after the COVID-19 pandemic (Jordão & Fernandes, 2022). According to the European Automobile Manufacturers' Association (ACEA), Portugal has 5 production and assembly plants, dedicated to the production of several vehicles as is possible to visualize in Table 1 (ACEA, 2022). These plants belong to several OEMs: Stelantis, located in Mangualde; Toyota Motor Europe, located in Ovar; Volkswagen AG, located in Palmela; Daimler Group, located in Tramagal, and Caetanobus, located in Vila Nova de Gaia.

Table 1 - Sum-up of Portuguese production and assembly parts. Source: Adapted from (Jordão & Fernandes, 2022)

Localization	Manufacturer	Type of Production	Brand
Mangualde	STELANTIS	Light Commercial Vehicles	Peugeot, Citroën
Ovar	TOYOTA MOTOR EUROPE	Light Commercial Vehicles	Toyota
Palmela	VOLKSWAGEN AG	Passenger Cars	Volkswagen, Seat
Tramagal	DAIMLER GROUP	heavy duty vehicles	Mitsubishi Fuso
Vila Nova de Gaia	CAETANOBUS	Buses	Caetano, Cobus

In 2020, the automotive sector generated 7.6 billion euros, representing 3.8% of the GDP and 14.2 % of the national exports of goods (Jordão & Fernandes, 2022). This reflects the highly exporting character of the automotive sector in Portugal, that exported 82.8 % of its total production in that year. The main destination markets are Germany, Spain, Italy and France, which encompassed about 75.4% of exportations made in the subsector of car production (Jordão & Fernandes, 2022). It is important to highlight the importance of VW AE to this sector because only this plant generated in 2021 3.1 billion euros in sales, representing 5% of the national exports and 1.5% of the GDP (VW Group, 2022). In Portugal, the automotive sector is composed of several subsectors, namely: the production of automobile vehicles; the production of bodies, trailers and semi-trailers; the production of electric and electronic equipment for automobile vehicles and the production of components and accessories for automobile vehicles (Jordão & Fernandes, 2022). In Appendix A, Figure A. 2, is possible to verify the distribution of companies, workers, gross value added (GVA) and exports within the subsectors. This figure also shows that the subsector correspondent to the production of components and accessories for automobile vehicles is the one that not only employs more workers but also generates a higher GVA and contributes the most to exports (Jordão & Fernandes, 2022).

In terms of automotive production, in 2020, 264,238 vehicles were produced in Portugal (Fábio Carvalho da Silva, 2021), with the proportion assigned to each OEM explicit in Appendix A, Figure A. 3. Once again, the leadership of VW AE is shown, being this plant responsible for 72.66% of the total national car production.

2.2 Semiconductor industry

2.2.1 Semiconductor definition, impact and main characteristics

Semiconductors are more and more used in modern cars to perform a variety of functions, such as safety and driver assistance, connectivity or entertainment (Kumar, 2021). However, they are also used in many other industries besides the automotive, such as telecommunications, computing, healthcare, military systems, transportation or energy, being a critical part of every electronic device

(Semiconductor Industry Association, 2022). Indeed, they are considered the brain of modern electronics because they foster the development of new technologies that are essential to the growth and competitiveness of economies. Without semiconductors, there would be no computers, cars, smartphones, game consoles, drones or advanced medical equipment (Semiconductor Industry Association, 2022). Therefore, these components play a crucial role in contemporary society. Semiconductors, also mentioned as integrated circuits or microchips, are made from pure elements, especially silicon, or other components like gallium arsenide, and are formed by hundreds of components (Semiconductor Industry Association, 2022). This industry is generally organized in two main stages: design and manufacturing (Semiconductor Industry Association, 2022). Some companies focus only on the design stage, and these are referred to as "fabless" firms, while other companies focus exclusively on manufacturing, and are called "foundries." There are also some semiconductor firms that do both design and manufacturing, called Integrated Device Manufacturers (IDMs) (Matsuo, 2015). The semiconductor industry invests consistently in R&D since companies are obsessed with obtaining "faster, smaller and cheaper" microchips, in order to meet the requirements of technological companies, that seek continuous innovation and product improvements (Forster et al., 2013). In this way, the semiconductor industry is capital-intensive, with the cost of a manufacturing facility reaching 5 billion dollars (Mönch et al., 2013). This happens because machinery is very expensive and the manufacturing process is very complex, requiring up to 700 single process steps and up to 3 months to produce the final microchip (Mönch et al., 2013). Semiconductor devices are produced in specialized facilities called cleanrooms that need ultra-clean air-circulation systems (Kumar, 2021). This procedure is required to reduce particles in the cleanroom air because particles originate defects in the nanometre scale manufacturing processes used to manufacture semiconductors (Kumar, 2021). Cleanrooms and semiconductor manufacturing tools, usually called wafer fab equipment, are also quite expensive. Furthermore, it is also a labour-intensive industry because it needs a wide range of workers, particularly specialized workers. Contrary to other industries, where the production stage is mainly performed by non-qualified employees, the semiconductor industry needs several specialized workers, particularly engineers, because the production processes are meticulous (Barbe et al., 2018). The chip´s design stage is even more complex and requires very specific know-how in artificial intelligence, quantum computing and other cutting-edge technologies, which requires extremely qualified people (Semiconductor Industry Association, 2022).

2.2.2 Semiconductor's market and main players

In terms of market, the leading semiconductor companies (including fabless, foundries and IDM) in 2021, by sales revenue, are located in US and Asia-Pacific, namely Taiwan and South Korea (Statista, 2022e). As is possible to visualize in Appendix A, Figure A. 4, the top-3 companies' ranking is led by Samsung, followed by Intel and the Taiwan Semiconductor Manufacturing Company (TSMC), respectively (Statista, 2022e). Nevertheless, if the focus is placed only on the production stage, a huge difference exists. In terms of production, the US is a minor player, included in the category "others", as Figure A. 5 in Appendix A illustrates (Statista, 2022d). In 2021, 88% of the global production of semiconductors is concentrated only in three countries in Asia-Pacific: Taiwan, South Korea and China. Taiwan is by far the most relevant foundry worldwide, responsible for 65% of global production. In 2021, the worldwide leader in terms of production is, by far, TSMC, which is responsible for more than 50% of the worldwide production of semiconductors, as is evident in Figure A. 6, Appendix A (Statista, 2022c). If the interrelations between the Figure A. 4 and Figure A. 6 are analysed, is possible to conclude that, despite Intel being the second major company in terms of sales revenue in 2021, it has no relevant representation in terms of production. In terms of market, TSMC, Intel and Samsung follow different strategies. Although Intel is not a relevant manufacturer, it still produces its chips and, as a result, it can be classified as an IDM (Mell, 2021). TSMC focuses only on the production stage, being classified as a foundry, and sells all the chips produced to other brands, being Apple its main customer (Mell, 2021). Samsung, the leader in terms of revenue sales in 2021, is also an IDM, which follows a hybrid strategy because invests deeply in the design stage and is also the second major foundry (Mell, 2021).

In terms of market segments, in 2020, the communication sector and technological firms that sell computers are the main clients of semiconductors, accounting for 63.5% of the market (see Figure A. 7, Appendix A) (Semiconductor Industry Association, 2021). Indeed, the automotive sector only buys 11.4% of all semiconductors produced, being only the fifth client. Therefore, the automotive sector is a minor client of the semiconductor companies and the bargaining power of automotive companies seems to be limited.

2.2.3 Semiconductor´s threats and risks

As was possible to verify in section 2.2.2, the semiconductor market is composed of a few big players, being a very concentrated market. This condition happens because it is a sector that demands a high initial investment (Mönch et al., 2013), skilled workers (Barbe et al., 2018) and continuous investments in innovation (Forster et al., 2013). Besides being concentrated in terms of players, it is also concentrated in terms of regions since the major semiconductor players are located mainly in 3 countries: Taiwan, South Korea and the United States. In terms of production, the market is even more concentrated, with 2 countries (Taiwan and South Korea) accounting for 83% of worldwide semiconductor production, as stated before (see Figure A. 5, Appendix A). This geographic concentration of semiconductors production causes long lead times, jeopardizing the delivery to the customers and originating backorders (Ramani et al., 2022). All these characteristics have implications for the stability of the market. Even a small disturbance in the production lines of TSMC or Samsung Electronics, the two major global foundries, could have a significant impact on the whole downstream SC and affecting companies in several echelons (Mell, 2021). Moreover, another risk faced by the semiconductor industry is the talent shortage. As this industry seeks constant innovation, it requires qualified tech talent to perform R&D roles, which sometimes is difficult to obtain (Mell, 2021).

2.3 Interface between the automotive and the semiconductor industries

2.3.1 Semiconductors in the automotive industry

As was stated before, semiconductors are more and more used in modern cars to carry out a wide range of functions, related to safety and driver assistance, connectivity or entertainment (Kumar, 2021). However, these components are not used directly by the OEM because they are embedded into modules. These modules are, in turn, integrated into several subsystems of the car that are delivered by the first-tier suppliers and are used to transmit the flow of information and execute orders (Matsuo, 2015). They are included in a variety of parts, for instance in climatronics, micro control units, displays, radar sensor, power steering, Modular Infointertainment Toolkit (MIB) and door modules. A climatronic is a fully electronic climate control system, which uses a computer system composed of semiconductors that help adjust air distribution, temperature and flow (Volkswagen, 2022). The control units are used in several systems of the vehicle, namely in the engines, to command all electronic orders. The display is responsible for the info entertainment and the radar sensor is an integral part of the advanced driver assistance system, deployed for blind-spot detection, lane change assistance, collision mitigation or parking aid (Infineon, 2022). Semiconductor modules of power steering are used to transmit the orders to the power train of the car and modules included in MIBs feed the display, being used for info-entertainment functions, such as internet connection, communication and navigation (Lindland, 2020). Door modules are placed inside the doors and are responsible for central locking, mirror adjusting or move up and down car windows (Continental, 2022). In this way, semiconductors are indispensable for current automobiles. However, with the introduction of hybrid and electric vehicles in the market and the future development of autonomous vehicles, the need for semiconductors is going to be more and more significant (Wu et al., 2021). As an example, while the cost of microchip parts in a traditional combustion engine does not exceed 100 dollars, in a hybrid vehicle this cost can exceed 1000 dollars (Parker & Thomas, 2013), which shows the future growth of semiconductors utilization in cars and the increment in the final market value of the product. Indeed, led by electrical vehicles and the introduction of automated driver assist systems, the automotive segment is considered the fastest-growing semiconductor market segment in the next decade, as stated in Figure A. 8, Appendix A (Kearney, 2022; Mckinsey, 2022). Thus, with this increase in the business relationships between the automotive and semiconductor industries, it is important that the interconnected SCs work efficiently and, foremost, they must be resilient, in order to cope with risks that can originate major future disruptions.

2.3.2 Risks and disruptions in the interface between the automotive and semiconductor industries

The recent global disruption in the semiconductor industry, induced by the COVID-19 pandemic, affected all industries, namely the automotive, and showed the fragile equilibrium existent in the whole semiconductor SC (Ramani et al., 2022). However, the disruptions in the interface between the automotive and semiconductor industries are not a novelty, as will be explored in the literature review (see section 4.2.1). In March 2000, a fire at a Philips semiconductor plant led to the disruption of semiconductor production, which originated a shortage of chips in the market and affected enormously the SC of Ericsson, causing an estimated total loss of 400 million dollars (Chopra & Sodhi, 2004). In 2011, the Tohuku disaster caused by a massive earthquake had severe consequences worldwide in the automotive and semiconductor industries (Matsuo, 2015). Toyota, for instance, was severed affected, suffering a disruption in production, dropping over 40,000 cars and costing 72 million dollars in profits per day (Pettit et al., 2013). Nevertheless, not all companies were severely affected by this catastrophe. Norrman & Wieland (2020) studied the impact of the disaster on Ericsson's operation and concluded that the SCRM process applied by the company was indispensable to limit the damages. The same company that in 2000 was severely affected by the fire at a supplier´s plant, could operate with almost no problem after the major disaster of 2011. This change resulted from the investment made by the company in the process of SCRM, which allows it to identify, assess, treat and monitor risks. Indeed, the ability of Ericsson to activate its Ericsson Supply Chain Management Task Force immediately after the disruption and the good crisis management process were critical to the good performance of the company (Norrman & Wieland, 2020).

Overall, the market of semiconductors is highly exposed to risks and can be easily threatened. The great concentration of the market in terms of players and geographical area originates long lead times and difficulty in complying with customer orders, as explained before (Ramani et al., 2022). Besides, despite being considered the fastest-growing semiconductor market segment in the next decade, the automotive segment will continue to be less important in the customer portfolio of semiconductor companies than the computing and communications segments (see Figure A. 8, Appendix A) (Mckinsey, 2022). With the migration to electric cars and hybrid cars, the dependency of automotive companies on semiconductors will also raise (Wu et al., 2021). Furthermore, the automotive industry has its own risks, associated mainly with JIT and JIS policies, as was explained before. These production systems are characterized by low levels of inventory (Graf, 2006), which could jeopardize production if shortages occur. Therefore, countermeasures like contingency plans to avoid disturbances and mitigate the impact of a possible SCD must be built (Wagner & Silveira-Camargos, 2012). The paradigmatic example of Ericsson showed the importance of the SCRM process to cope with disruptions and raise the resilience of companies (Norrman & Wieland, 2020). As SCDs are expected to increase in number and severity in the future (Pereira et al., 2020), companies must be aware of the risks that their SCs face and how to deal with them. Thus, this study intends to analyse the SC of semiconductors in the automotive industry, raising awareness of the importance of the SCRM process to cope with disruptions and build resilience in OEMs.

The following chapter will be dedicated to the case study developed in VW AE and intends to understand the semiconductor crisis problem that VW AE´s SC has been facing since 2020. In this way, it is going to be performed a contextualization of the VW group and the VW AE, namely its main business units, organizational structure, production and markets. Then, VW AE´s SC is going to be characterized and the boundary of the study will be established. The chapter will end with an analysis of VW AE´s semiconductor SC and the impact that the semiconductor crisis has had on the company.

3 Case Study: Volkswagen Autoeuropa

3.1 Volkswagen Group

VW Group is currently one of the biggest automobile manufacturers in the world, being the second one in terms of market share in 2021, only behind Toyota (Statista, 2022b). The origin of the group goes back to 1937, when the government of Germany, under the control of Adolf Hitler, founded an automobile company named *Volkswagenwerk* or *The people´s car company* (History.com Editors, 2021). The main goal of the company was to build and commercialize a car that could be purchased by the broad masses of the population in Germany. Ferdinand Porsche (1875-1952) was the engineer responsible for developing the first models despite the drawing being mainly inspired by the work developed by Hans Ledwinka for the firm Tatra (Encyclopaedia Britannica, 2022).

With the new group strategy, "NEW AUTO – Mobility for Generations to Come", VW intends to be a major driver of digital transformation and a software-driven mobility provider, able to redefine mobility and to do business climate neutrally and conscientiously (Volkswagen Group, 2021b). Nowadays, VW, whose headquarters are located in Wolfsburg (Germany), is disseminated worldwide, with 120 plants spread in Europe, Asia, America and South Africa (Volkswagen Group, 2021a). VW is composed of nine car brands plus Ducati, inserted into 3 categories: volume, premium and sport. The first category is formed by Volkswagen, Volkswagen Commercial Vehicles, Skoda, Seat and Cupra while the second one encompasses Audi, Lamborghini, Bentley and Ducati, and the sports category includes Porsche (Volkswagen Group, 2021a). Furthermore, VW Group also has other brands and business units, such as the trucks companies MAN and Scania or the pioneering on-mobility demand company MOIA (Volkswagen Group, 2021a).

In numerical terms, in 2021, VW group produced approximately 8.9 million cars and sold 8.3 million, resulting in 250,200 million euros in sales revenue and 15,428 million euros in earnings after taxes (Volkswagen Group, 2021a). This year, VW was composed of a huge network of employees worldwide, totalizing, approximately 672,800 employees (Volkswagen Group, 2021a).

3.2 Volkswagen Autoeuropa

3.2.1 History and evolution

VW AE is an automotive plant of the VW Group, located in Palmela, Setúbal, Portugal. The history of VW AE, which has several important milestones, represented in Figure 3, began in 1991, when an investment contract between the Portuguese state and the joint venture formed by Volkswagen and Ford was signed, to share resources in the production of multi-purpose vehicles (MPV) of both groups: Volkswagen Sharan, Seat Alhambra and Ford Galaxy (Volkswagen Autoeuropa, 2021). The initial investment was 1,970 million euros and is considered to be the biggest foreign investment ever made in Portugal. In 1995, the plant was inaugurated and the production of the three aforementioned vehicles started. Later on, in 1999, the joint venture between the two automobile groups ceased and the VW group acquired all participation in VW AE, which would generate the end of production of Ford Galaxy, consummated in 2006 (Volkswagen Autoeuropa, 2021). In that year, VW AE initiated the production of VW EOS, a convertible car. In 2008 the production of the VW Scirocco, another new model, began (Volkswagen Autoeuropa, 2021). The next year, 2009, was an important year for VW AE because the One-Line-Concept was implemented, which allowed the production of the three types of cars (MPV, EOS and Scirocco) in one single line, rising flexibility on the shop floor (Volkswagen Autoeuropa, 2021). Until then, each type of model had a single line exclusively dedicated to each one. In 2015 the end of production of EOS occurred and in 2017 the Scirocco also stopped being produced. 2017 was a changing year for VW AE since the model that now represents the core business of the plant, the sports utility vehicle (SUV) called T-Roc was launched (Volkswagen Autoeuropa, 2021). This model release meant a paradigm shift for the Palmela plant, which had to increase its production capacity, changing its daily journey from 16 hours of production to 24 hours of production, to be able to reach a daily average production of 890 vehicles (Volkswagen Autoeuropa, 2021). In 2021, VW AE celebrated its 30th anniversary (Volkswagen Autoeuropa, 2021).

Figure 3 - Main milestones of VW AE. Source: VW AE

3.2.2 Business units

VW AE is composed of three business units: automotive production, Press Shop, and Tool and Die (Volkswagen Autoeuropa, 2021). The first is the main business unit and the one that currently constitutes the core business of VW AE, corresponding to the production of the automobile models VW T-ROC, VW Sharan and Seat Alhambra (Volkswagen Autoeuropa, 2021). The business unit Press Shop is responsible for producing parts not only for cars that are produced in VW AE, but also for those produced in other factories of the group. Therefore, VW AE sells parts, such as side panels, doors and roofs to other factories of the VW group, constituting another source of revenue (Volkswagen Autoeuropa, 2021). In 2021, this unit employed 108 employees and approximately 21 million parts were produced and exported to factories in Europe, Asia and South Africa (Volkswagen Autoeuropa, 2021). At last, there is also the Tool and Die business unit, whose main objective is the production of tools that are going to be used mainly to produce the parts in the Press Shop. As a result, this business unit works also as a complement and an additional revenue source. In 2021, this unit generated approximately 23 million euros in revenues and was formed by 220 employees (Volkswagen Autoeuropa, 2021).

3.2.3 Organizational structure

According to data from January 2022, VW AE is composed of 5,124 employees, dispersed in a vertical organisational structure formed by eight business areas under the administrative board, as shown in Figure 4 (Volkswagen Autoeuropa, 2021). Each of these business areas, or departments, works in an interconnected and collaborative manner to increase the plant´s efficiency in terms of cost, time and quality, to produce the final products.

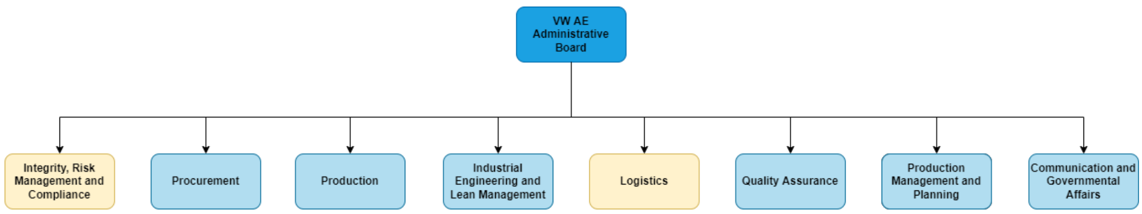

Figure 4 - VW AE Organizational Structure. Source: VW AE

Despite all departments playing an important role in the organization, this study is going to be developed mainly within the scope of the logistics business area. This department is mainly responsible for planning, executing and controlling the effective and efficient flow of information, materials and other services from the starting point to the point of consumption to satisfy the customer´s requirements (Volkswagen Autoeuropa, 2021). The logistics department itself is divided into several sub-departments or teams, as represented in Figure 5. Moreover, information within the scope of the Integrity, Risk Management and Compliance Department is also used in this work.

This project is mainly developed in the Supply Chain and Transports Division, which has the goal of ensuring the supply of all parts needed for the production of the sub and final products (Volkswagen Autoeuropa, 2021). In this way, this team assures the management of the materials flows from the suppliers or sub-suppliers till the delivery in the plant, as well as the control of critical parts inside the plant. Moreover, another crucial function of the team is the request of orders to the suppliers, not only the JIT suppliers, located mostly in the adjacent industrial park, but also the shelving suppliers, doing the traffic and invoice control. Lastly, inside the division, a team is dedicated to plan the transport needed to transport the supply parts.

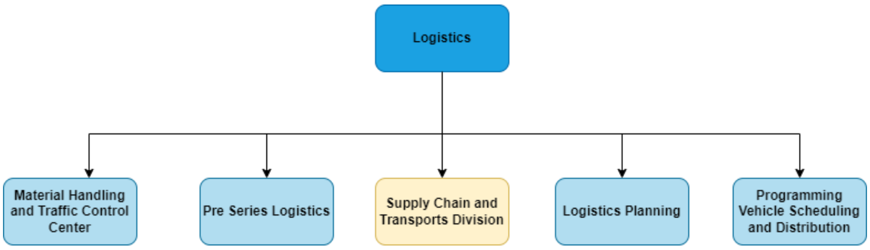

Figure 5 - Logistics Department Structure. Source: VW AE

3.2.4 Production and markets

In 2021, VW AE produced 210,754 vehicles, referring the great majority, approximately 95%, to the T-ROC model and only 5% corresponding to MPV models (VW Sharan and Seat Alhambra) (Volkswagen Autoeuropa, 2021). VW AE has currently a daily capacity of production of 890 vehicles. In 2021 VW AE worked under its capacity, mainly due to the restrictions and consequences originated by the COVID-19 pandemic. With the successive lockdowns and contingency measures, the workforce was restricted and the plant was even forced to stop. Moreover, the semiconductors' crisis was also a major problem, that constrained some parts' supplies and limited the cars produced, as it is going to be explained in section 3.2.6.

As Figure 6 illustrates, in 2021 the percentage of cars exported totalized 99.2 % of VW AE´s production (Volkswagen Autoeuropa, 2021). The main destination was Germany, which received 22.8% of the cars produced in the plant, followed by Italy. Outside Europe, Japan and Turkey were the most representative markets. This shows the high exportation capacity of AE, which represents 5% of the global Portuguese exportations. As it was mentioned before, in terms of sales, in 2021, AE generated 3,1 billion euros in sales and had an impact of 1.5 % on the national GDP. Table 2 presents a summary of these facts and numbers.

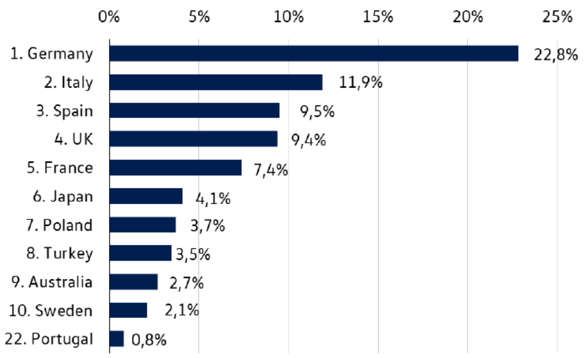

Figure 6 - VW AE main exportation markets. Source: VW AE

Table 2 - Relevant Facts and Numbers. Source: VW AE

AE Characterization	2021
Production Volume (10^3 units)	210.8
Production for Exports (%)	99.2%
Impact on Portuguese Exports	5%
Impact on GDP (%)	1.5%
Sales volume (billion €)	3.1

3.2.5 VW AE's SC

VW AE's SC is composed of a wide set of entities, that encompass, for instance, suppliers, carriers, consolidations centers, the plant, distribution centers and clients. Nevertheless, the focus of this case study will be on the upstream part of VW AE's SC, this is, on how VW AE should manage the relationship between the suppliers, namely first-tier suppliers, in order to perform an effective SCRM towards resilience. In Figure 7, it is possible to visualize the generic scheme of the VW AE´s SC and the focus that it is going to be placed on the plant and its first-tier suppliers, being this considered the study boundary.

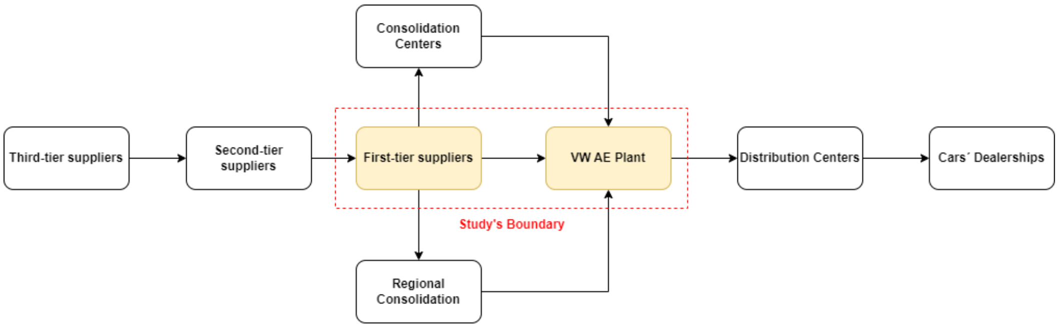

Figure 7 - Overview of VW AE' SC and study´s boundary.

VW AE has a wide range of suppliers, that are divided into two main categories: JIT/JIS suppliers and distant suppliers (shelving suppliers). The first category includes the suppliers that belong to the industrial park located nearby the plant. These suppliers, in general, are responsible for delivering finished subsystems, such as wiring harnesses, driving assistance or transmissions, directly to the final assembly lines. The second category encompasses the supply of small parts or other components that are located far away from the plant and that are not supplied by the JIT/JIS suppliers. At the end of 2021, VW AE had a network formed by 23 JIT suppliers and 657 distant suppliers. As it is possible to visualize in Figure 8, in terms of regions, the majority of suppliers are located in Western and Central Europe, followed by the Iberian Peninsula, where not only some distant suppliers but also the JIT suppliers are located. It is important to underline that some suppliers are located in other regions of the world, such as Asia and America. However, as these regions were not representative in 2021, they are not represented here.

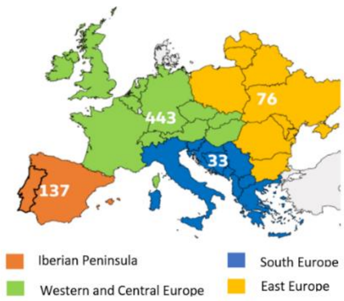

Figure 8 - Main regions of VW AE's Suppliers in Europe. Source: VW AE

In terms of inbound flows, as Figure 7 also shows, three forms of doing the transportation between the first-tier suppliers and the VW AE plant exist. If the supplier is located in the industrial park nearby VW AE or if exists enough load to fill in a complete truck, i.e., Full Truck Load (FTL), a direct shipment to the plant is performed. On the other hand, if there is not enough load to fill in a truck, the shipment is done via consolidation. Here, there are two possibilities, depending on the location of the suppliers. If the first-tier supplier is located in Portugal, Spain or France, a regional consolidation by a carrier or a Third-Party Logistics company (3PL) is done, being the 3PL responsible for consolidating requests from several suppliers and for the transportation to the plant. If the first-tier supplier is located in other countries, a consolidation via consolidation centres is performed, working as cross-docking platform to transfer the materials. Then, the materials are shipped to VW AE.

In terms of outbound flows, as it is represented in Table 3, there are two possibilities to transport the cars produced to the distribution centers: road transportation and sea transportation. Road transportation, done in trucks, currently represents only 21.8% of the total volume of cars that leave the plant while sea transportation represents the majority, 78.2%. On the one hand, the cars that leave the plant by truck can be transported either to seaports in Spain, like Barcelona, Vigo and Santander, or to distribution centers. On the other hand, the cars that are transported through the Port of Setubal leave the plant by train. After this short voyage from VW AE to the port, they are transported by sea to other ports and then from that to the distribution centers. The main destiny ports, represented in Figure 9, are located in the United Kingdom, Italy, Belgium and Germany, being the most important located in Emden, Germany. The distribution centers are then responsible for the transportation to the car dealerships.

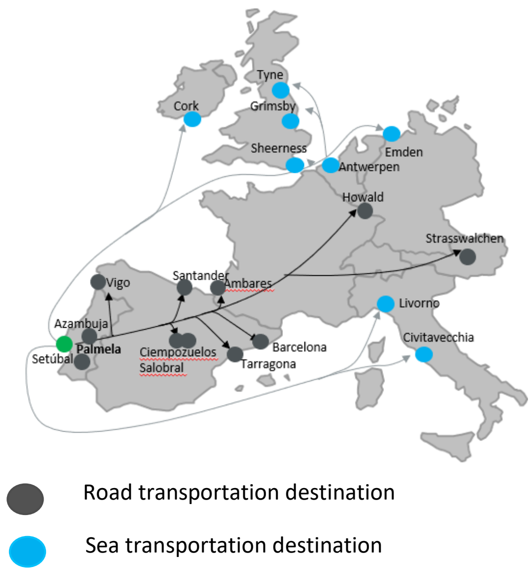

Figure 9 - Transportation destinations. Source: VW AE

Table 3 - Transportation Modes and Destinies of Cars. Source: VW

Transportation Mode and Destinies	Percentage allocated to each transportation mode in 2021 (%)
Total of Road Transportation	21.8%
Portugal	0.8%
Spain	9.0%
France	7.4%
Luxemburg	0.3%
Austria	0.3%
Port of Barcelona	2.2%
Port of Vigo	0.5%
Port of Santander	1.3%
Total of Sea Transportation through the Port of Setubal	78.2%

3.2.6 Semiconductors SC and impact on VW AE

The semiconductor disruption induced by the COVID-19 pandemic also affected VW AE. Indeed, this topic, together with the COVID-19 lockdown and the lack of capacity, were considered the main negative highlights that affected the value chain of VW AE in 2021. As was explained before, the semiconductors are integrated into different electronic subsystems provided to the cars´ manufacturers by the first-tier suppliers. Therefore, with the semiconductors' supply crisis, the first-tier suppliers suffered constant disruptions because their providers were not able to provide them. This shortage of microchips in suppliers and sub-suppliers affected then VW AE, which could not finish some of its cars. When the shortage was of indispensable electronic subsystems, called job stoppers, without which the assembly could not proceed, the line was forced to stop until these subsystems were supplied. On the other hand, if the scarcity was of components or parts that could be assembled *a posteriori*, the assembly continues but the car leaves the assembly stage incomplete. Thus, the vehicles were parked incomplete and then, when the missing parts arrived, the car would be finished. This process of finishing the cars *a posteriori* has high costs to the plant, which, in addition to not being able to deliver the cars to customers, also has to allocate human resources and extra time. Besides, there is also a limited capacity of the park, which should be complied with. Nevertheless, this process is much cheaper than stopping the assembly line, which only occurs when all the possible solutions are inviable and do not produce results. Stopping the assembly line is the worst scenario in every assembly line because it implies massive costs. The incomplete parked cars are indeed an indicator that helps VW AE to monitor the impact that missing parts have on its business. In 2021, 11,324 incomplete cars were parked. This happened mainly because of several shortages of semiconductor components, which are included in climatronics, control units, displays, radar sensors or door modules, as previously mentioned.

One key performance indicator (KPI) that reflects the impact of the semiconductor crisis on VW AE's cost structure is the *Beschaffung Neben Kosten* (BNK). The BNK is an indicator that measures the additional costs associated with the purchase of components/parts. Thus, it encompasses the costs associated with the rental of packaging, transport and the supply of the parts to the assembly line. In Figure 10, the red bars represent the extra costs associated with factors that were not considered in the initial cost plan while the green bars represent savings that were not initially expected. As it is possible to verify in Figure 10, the semiconductors were responsible for 0.52 million euros in additional costs to purchase, being the second major cost factor. If we decompose this value, we observe that three subfactors are responsible for this cost:

- Firstly, the especial transports, internally named SOFAs, were responsible for 0.36 million euros in 2021. These transports are made when there is a problem with normal transportation or an urgency regarding the parts' supply, namely when a shipment of parts is indispensable to not stop the assembly line. These especial transports include air freight, on-board carriers or transport in vans.

- Secondly, there is the extra cost associated with the warehousing of trucks that are not initially planned, which in 2021 represented a cost of 0.103 million euros. This occurred when VW AE requested carriers or 3PLs to keep the trucks in their installation due to the lack of warehousing capacity in VW AE plant.
- Finally, the last factor is related to demurrage. Demurrage includes the paralysation costs of trucks that VW AE has to pay to carriers. If the trucks arrive to unload the shipment within the time window established in the contract but have to wait to do it because a great congestion in the inbound flows exists, VW AE has to pay a value to compensate for the time wasted by the carriers. As it is possible to acknowledge, this subfactor only represented 0.053 million euros in 2021.

However, it is important to note that the semiconductor crisis has also led to the stop of assembly lines, which had millions of euros in losses. Besides not being able to produce and deliver the cars ordered, VW also had to continue to pay its workers and sometimes even had to pay indemnities to some clients. In terms of savings, the transport optimizations performed by the SC transport team allow VW AE to save 0.29 million euros in 2021 and the chargeback, related to the money paid back by the supplier to VW AE, saved 0.11 million euros.

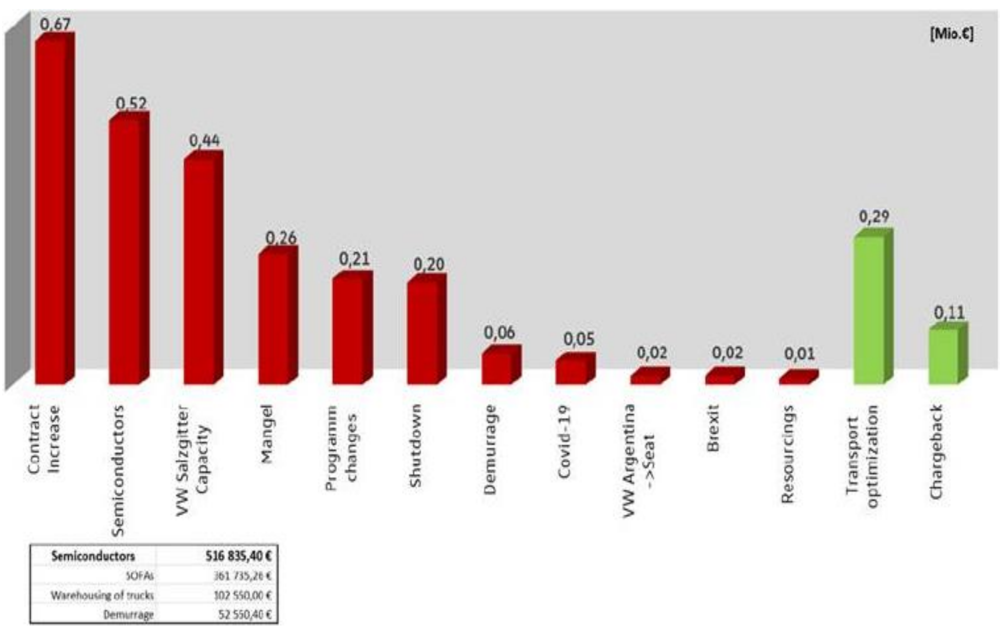

Figure 10 - BNK Performance Indicator for 2021. Source: VW AE

4 Literature review

This literature review has the main objective of investigating the concepts associated with the problem previously stated, presenting the major research topics that have been addressed by researchers. As a result, the most relevant ideas related to disruption management are going to be studied, in order to examine which concepts and models are suitable to analyse the semiconductors' disruption in the automotive industry. In this way, this chapter is divided into several sections, which encompass different but interconnected research avenues. Firstly, a brief explanation of two important concepts that are going to be constantly mentioned (supply chain management and risk management) is presented. Then, the concept of SCD is going to be defined and analysed, presenting the main sources and some important real cases, as well as studying the impact that a disruption can generate and the propagation effect that can be originated, affecting the whole SC. Later, a comprehensive review of SCRM is going to be performed, studying the entire process, which involves SCRI, SCRA, SCRT and SCR monitoring. Finally, the literature review ends with a review of the concept of SCRES, namely, its relationship with SCD and SCRM.

4.1 Important concepts

The concept of Supply Chain Management (SCM) was recognised for the first time by Oliver & Webber (1982) and from that moment onwards has been suffering a deep evolution and several authors have been presenting their definitions. According to Tang (2006), who combined the definitions of several authors, SCM is defined as "the management of material, information and financial flows through a network of organizations (i.e., suppliers, manufacturers, logistics providers, wholesalers/ distributors, retailers) that aims to produce and deliver products or services for the consumers. It includes the coordination and collaboration of processes and activities across different functions such as marketing, sales, production, product design, procurement, logistics, finance, and information technology within the network of organizations".

The concept of risk has been also extensively studied by researchers. One of the most cited definitions is the one proposed by March & Shapira (1987) that considered a risk "as the negative variation in business outcome variables such as revenues, costs, profits, etc". In general, the majority of researchers agree that the risk of occurring a specific event results from the conjunction of two factors: the probability of occurrence of that event; and the impact that the event can generate. According to Aqlan & Lam (2015), risk management (RM) is the process that "should be able to identify, measure and prioritise the different risks in the SC, develop proper mitigation strategies, and monitor and control these risks".

4.2 Supply Chain Disruption (SCD)

4.2.1 Definition, main sources and example case studies

SCD arose as an emerging research area at the beginning of the 21st century, mainly due to the contributions of several authors, such as Kleindorfer & Saad (2005), Hendricks & Singhal (2003), Tomlin (2006), Tang (2006), among others. It is defined as an unexpected and unpredictable occurrence that affects the usual flow of goods, materials and information along the SC (Craighead et al., 2007). During the last two decades, several major disruptions have been studied by researchers, who present three main categories of sources: natural disasters, man-made disasters and severe legal disruptions (Xu et al., 2020). In the first category, it is possible to highlight earthquakes, hurricanes, volcanic eruptions, floods or storms. Regarding to man-made disasters, must be considered terrorism, economic crisis, technology revolutions, labour strikes, wars, pandemics or political and social instability. Severe legal disruptions can be originated, for instance, by demanding environmental laws and targets. In the literature, there is a wide range of disruptions that have affected SCs, locally or globally. In March 2000, a fire at a Philips semiconductor plant led to the disruption of production, which originated a shortage of chips in the market and affected enormously the SC of Ericsson, which estimated a total loss of 400 million dollars (Chopra & Sodhi, 2004). In 2010, the volcano eruptions of *Eyjafjallajökull*, in Iceland, disrupted air transportation to and from Europe, leading to the cancelation of more than 60,000 flights and causing a severe negative impact on the world economy, with 1.7 billion dollars of estimated loss (Yoo & Yeo, 2016). The year of 2011 was, undoubtedly, one of the most difficult years which concerns global disruptions. Firstly, on March 11, a massive earthquake occurred on the Pacific coast of Tohuku (Japan), followed by a tsunami that caused the Fukushima nuclear disaster. This triple-disruption event had consequences worldwide in several industries and SCs, namely in the automotive and semiconductor industries. Toyota was severely affected, suffering a disruption in production, dropping over 40,000 cars and costing 72 million dollars in profits per day (Pettit et al., 2013). Then, in October of the same year, a catastrophic phenomenon of flooding happened in Thailand, causing damage to the SC of computer manufacturers and disrupting SCs of Japanese automotive enterprises, which had plants or high supplier dependencies in this country (Chopra & Sodhi, 2014). During the last decade, the civil war in Syria has originated humanitarian logistic issues in several countries in the EU and the Middle East, which had to modify their SC coordination mechanisms from helping people on the move to supplying refugee camps and other aggregated groups. More recently, the COVID-19 pandemic is considered one of the severest disruptions faced in human history because it has created a massive global crisis in breaking countless SCs worldwide (Merih Araz et al., 2020).

4.2.2 SCD impact

Regardless of the type of event, a disruption has always an impact, that can be individual, local or global. An individual impact is relatively circumscribed, affecting only one echelon of the SC, for instance, a specific supplier. A local impact is limited to a specific region but affects several entities or partners of the SC, such as a workers' strike instigated by a new labour legislation of a state. A global impact is non-limited and widely spread, affecting all entities of a SC at the same time (Katsaliaki et al., 2021). Ramani et al. (2022) identified the need of studying systemic disruptions, that have a global impact on the entire SC of several industries, such as the semiconductor crisis, induced by the COVID-19 pandemic, which has been a worldwide impact on the automotive industry. According to Parast & Shekarian (2019), the high degree of complexity and instability of current SCs originates an impact on companies' performance whenever a SCD occurs. The loss of revenues is ranked in the first place as the major consequence of disruptions to enterprises during the year of 2021 (Business Continuity Institute, 2021). In this way, almost three-quarters of organizations experienced severe, some or limited impact due to loss of revenues. However, besides the economic pillar of sustainability, extensively studied, a SCD also affects the social pillar. The majority of big disruptions has a high impact on people´s lives. In 2016, for example, around 28,000 workers were dismissed or moved to part-time jobs due to a legal dispute between the car consortium VW and some of its suppliers, which caused an interruption of production in six facilities of the group in Germany (Dolgui et al., 2018). In Table B. 1, Appendix B, several well-known disruptions in SCs are summed up as well as their impacts (Dolgui et al., 2018).

4.2.3 SCD propagation and the Ripple Effect

In general, a major disruption has a huge impact on SCs and it is very difficult to limit the impact to one singular echelon or even to a small group of entities. In this way, it is common that the impact and consequences of SCDs spread along with the SC, propagating downstream and affecting the performance of all entities, instead of being limited and circumscribed. This is the emergent concept of the Ripple Effect, which is considered now a specific area of SCD. In general, this phenomenon affects the performance and compromises the profitability of a company, diminishing the revenues and leading to the loss of brand reputation and market share (Dolgui & Ivanov, 2021). The ripple effect is also named as *snowball effect* and *domino effect* and it is usually originated by complexity in SC and the consequent pressure on velocity and efficiency (Mishra et al., 2021). Recent examples of the ripple effect are the following:

1. The disruption originated by the obstruction of the Suez Canal between the 23rd and 29th of March 2021 caused enormous chaos to the international trade market, jeopardizing

thousands of shipments around the world, that had to re-route their trips to Europe around Africa. A loss of 400 million dollars per hour was estimated in global trade (LaRocco, 2021).

2. The COVID-19 pandemic has affected a wide range of different SCs, causing several disruptions worldwide, impacting the global economy and leading to massive chaos (Merih Araz et al., 2020). In this way, the COVID-19 outbreak effects had a gigantic repercussion, testing the resilience and robustness of industries, that had to face numerous production halts and supply shortages (Ivanov & Dolgui, 2020).

The ripple effect has been increasingly studied in the last decade as a new research hotspot in disruption management. Ivanov et al. (2014) are considered the first authors to explore this designation in depth, presenting a disruptive paper that addresses the ripple effect through a dynamic framework, which interprets a SC as a dynamic controllable system described using differential equations. Moreover, the trade-off between flexibility, resilience and efficiency was analysed and some future research gaps were pointed out, such as the need of building a specific model taxonomy since there is no consensus on the definitions of terms related to the SC dynamics. More recently, some studies to quantify the ripple effect have been developed. Hosseini & Barker (2016) proposed a Bayesian Network methodology to evaluate the selection of a supplier, in order to quantify the suitability of suppliers taking into account not only economic and environmental criteria, but also the resilience criterion. The model developed quantifies resilience in terms of absorptive, adaptative and restorative capacities. Absorptive capacity is defined as the ability of a system to absorb shocks from disruptive events and can be developed through proactive planning or pre-disaster strategies. Adaptative capacity is the ability of a company to adapt itself after a disruption in order to diminish the negative consequences in companies' performance. Restorative capacity is the ability of a company to recover permanently from a disruption. While absorptive capacity is related to proactive strategies (strategies implemented before the disruption), adaptative and restorative capacity are associated with reactive strategies (strategies implemented after the disruption) (Hosseini & Barker, 2016). A new promising research topic, that hasn´t received yet much attention, is the relationship between the ripple effect and the bullwhip effect. The bullwhip effect, also called "demand amplification" or "variance amplification", is the effect caused when order variability is amplified as one moves upstream in the SC (Wang & Disney, 2016). This effect is mainly caused by demand uncertainty and variability and it is responsible for a wide range of inefficiencies along with the SC, such as the accumulation of inventory and backorders. Dolgui et al. (2020) developed a comprehensive study that analyses in depth the interrelations between the bullwhip effect and the ripple effect. The authors concluded that the ripple effect can be, indeed, a driver of the bullwhip effect and that this last one can be originated by a major disruption, with an impact not only upstream but also downstream. Therefore, managers must take into consideration the interactions that can happen between the two effects after a disruption occurs.

4.2.4 Semiconductor disruption in the automotive industry

The semiconductor shortage that caused a major disruption in the automotive industry during 2020-2022 had a variety of causes and produced several effects. The main cause might have been the great imbalance between supply and demand generated by the COVID-19 pandemic (Wu et al., 2021). At the beginning of 2020, the lockdown of a large part of the world's population, namely in countries such as Taiwan and South Korea, the world's main producers of chips, led to a disruption in the production of semiconductors. The measures to prevent and control the pandemic have led to the isolation of many workers and the cancellation of many shipments of goods, whether by air or sea transport. Therefore, a huge number of foundries decreased its level of production. The automobile industry was also forced to reduce or even stop its production, not only because of resource constraints, but also due to the decrease in demand that occurred because people were confined at home. Therefore, as the production of cars decreased significantly, the need for chips was very low, which led to a decrease in orders from the automotive industry to its suppliers. Meanwhile, with the migration to online classes and remote work, the consumption of electronic goods such as computers, smartphones, monitors or game consoles has increased exponentially, which has induced dramatic increases in microchips' orders by large technology companies. Thus, due to the exponential increase in demand for chips from companies that sell electronic goods and the decrease in demand for chips from the automotive industry, foundries that supplied the automotive sector changed their production lines and assigned their resources to the production of chips aimed at electronic goods. This change further reinforced the preference of producers for the production of chips aimed at their most representative markets (communications, computers and consumer electronics)(Wu et al., 2021).

Ramani et al. (2022) developed a comprehensive paper that presented a thematic model of the causes and effects of the semiconductor crisis, which is going to be summed up hereafter. These authors identified five causes that were responsible for the semiconductor shortage:

1. Global Pandemic – Due to the global pandemic, governments were forced to impose restrictions on the movement of people and goods, and the non-priority sectors were forced to shut down. The automotive companies reduced their capacity or even suspended their production in some factories, not only to prevent the spread of infections but also because the demand for cars suffered a high decrease (Ramani et al., 2022).

2. Supply disruptions – Several supply disruptions in semiconductors productions facilities also contributed to worsening the situation. A cold snap in Texas at the beginning of 2021 impacted the production at the Samsung, Infineon Technologies and NXP semiconductor plants (Inagaki & Campbell, 2021) and a fire at Renesas Electronics Corporation in Japan damaged nearly two-thirds of the facility responsible for the production of automotive chips (Inagaki et al., 2021). Besides, logistical issues associated with shipping delays and ports' congestion amplified the consequences of these supply disruptions (Ramani et al., 2022).
3. Automotive SC complexity – The complexity associated with the multi-tiered automotive SC also aggravated the shortage problem. An OEM usually places orders with its first-tier suppliers like Bosh and Continental, who placed their orders with second-tier suppliers such as Infineon Technologies, NXP or STMicroelectronics. However, as these second-tier suppliers were unable to satisfy the orders with their own capacities, they had to place orders with large semiconductor foundries like TSMC (Pan, 2021) . Along with this complex SC, there were order cancelations, demand amplification and information delays that contributed to shortages spread (Ramani et al., 2022).
4. Chips Manufacturing re-alignment – Semiconductor manufacturers earn a higher margin producing high-technology chips used by consumer electronics companies instead of the low margins associated with the production of chips used by automotive companies. Therefore, when automotive companies stopped their semiconductor orders, chip manufacturers reallocated their production capacities exclusively to consumer electronics clients. As with the production of high-technology chips semiconductor manufacturers have higher margins, then they do not have incentives to alter their product mix, since they are operating already at full capacity (Ramani et al., 2022).
5. Post-pandemic Recovery – As the confinements were ending, the demand for cars began to increase since people preferred to use their own vehicles instead of public transport, where they could get COVID-19 more easily. Therefore, OEMs began to produce cars and order more semiconductors from their suppliers. However, due to the change in the production mix of foundries and the fact that they were already working at maximum capacity, automotive suppliers informed OEMs that they were unable to meet the increased demand (Root, 2021).
6. Geopolitical Risk – The trade war between US and China also contributed to worsening the shortage problem of semiconductors. The US government imposed sanctions on Huawei Technologies and made a pact with TSMC to prevent the sale of semiconductors to Huawei and ZTE. In anticipation of this, Huawei started to stockpiling chips in 2019, which limited the capacity of other companies in obtaining semiconductors (Ramani et al., 2022).

Ramani et al., (2022) also identified four main effects associated with the chip crisis, which were:

1. Production Disruptions – As automotive suppliers could not meet the demand required by OEMs, automotive companies were forced to decrease their production or even shut down some facilities (Ramani et al., 2022).
2. Inflationary pressure – The semiconductor shortage and the higher shipping costs led to an increase in chip´s prices. Therefore, with this increase, automotive companies were also forced to increase the price of their cars. Besides, due to the absence of new car models, the price of used cars also raised (Smith & Stubbington, 2021). This global semiconductor shortage also induced an increase in consumer electronics prices (Kay, 2021b).
3. Labour Issues – Since OEMs were forced to shut down their plants during the post-pandemic recovery due to the semiconductor shortage, many automotive workers were fired or put on layoff (Ramani et al., 2022).
4. End-consumer and dealer issues – The shortage of chips also limited the customer´s choice. As OEMs were only able to produce certain vehicle models, car dealers could only sell a limited number and portfolio of cars (Kay, 2021a). This limitation induced a rise in the demand for used cars.

However, the COVID-19 pandemic exposed the fragile resilience that already existed in the SCs of semiconductor and automotive industry. This lack of resilience exists because of the distinct SC characteristics of these two industries, which are highly exposed when there is a significant disruption, like it happened in 2011 after the Tohoku disaster. Forster et al. (2013) developed a comprehensive paper that explains in detail the differences in SC characteristics between automotive and semiconductor industries, namely in terms of: cyclicity and volatility; product life cycle; supply of spare parts; quality; lead times; planning horizons and production flexibility. These SC characteristics are summed up in Table 4 and are going to be analysed hereafter.

Table 4 - Comparison of SC characteristics between Semiconductor and Automotive Industries. Source: Adapted from (Forster et al., 2013)

SC Characteristics	Semiconductor Industry	Automotive Industry
Cyclicity and Volatility	Very High	Moderate
Product Life Cycle	2-3 years	22 years
Supply of Spare Parts	Short	25 years
Quality	Moderate	Very High
Lead Times	10-16 weeks	2 weeks
Planning Time Horizons	6 months	Few Days
Manufacturing Flexibility	Very Low	High

1. Cyclicity and Volatility – In terms of cyclicity and volatility, there is a considerable difference between these two industries. In the semiconductor industry, the market cycles are very short, characterized by periods of rapid growth, followed by market falls and then an innovation period, that origin rapid growth, and so on. These types of market cycles are aligned with the market cycles of electronic devices, such as smartphones, the major market of semiconductors, that have very short cycles and high volatility. This diverges from the automotive industry that has a stable market cycle and quite predictable demand (Forster et al., 2013).
2. Product Life cycle – The product life cycle of these two industries is also distinct. The semiconductor industry is obsessed with technological progress, seeking for "smaller, faster and cheaper" microchips. In this way, the product life cycle of a semiconductor is short and once again aligned with the main clients of the industry (telecommunication and data processing companies). Generally, a new product is put on the market within 12/18 months and has a medium lifespan of 2/3 years. On contrary, a car has a long-life cycle, being produced in series for 5 years and having a medium lifespan of 15-20 years (Forster et al., 2013).
3. Supply of Spare Parts – Another difference between the two industries is related to the spare parts supply. On the one hand, the semiconductor industry does not have in its main priorities the supply of spare parts because, if a smartphone or computer becomes obsolete after two or three years, people tend to buy a new product, with an improved technology, that has smaller and faster semiconductors. However, if a car has a problem with an electric component, usually people tend to request a spare part that must have semiconductors with the same technology, instead of buying a new car. This poses extra challenges to the semiconductor industry that is obliged to supply spare parts with the same microchips to the automotive suppliers. Therefore, the foundry has to maintain a production line only dedicated to the automotive industry during all life cycle of a car (20-25 years). This means that this line cannot be updated with technological advancement and so cannot be used to produce chips for the telecommunication sector, which is not aligned with the motto of semiconductor companies of obtaining "smaller, faster and cheaper microchips" (Forster et al., 2013).
4. Quality – In the semiconductor industry, the rate of microchips produced without defects is about 95%, which does not compromise the safety and effectiveness of smartphones or laptops. However, in the automotive industry, the quality of microchips is critical to cars' safety and consequently peoples' lives. Therefore, the quality standards are extremely high and the rate of production without defects must be close to 100%. In this way, foundries

must assure that the semiconductors produced for the automotive segment fulfil this requirement, which is quite demanding and costly. This makes the automotive industry hesitate to update technology and as a result semiconductor companies are obliged to maintain older manufacturing technologies focused exclusively on producing microchips for the automotive industry (Forster et al., 2013).

5. <u>Lead times</u> – In terms of lead times, the two industries also present huge differences. While the lead time of a foundry is between 10 to 16 weeks because the production of chips is very complex, the OEM has the role of "10 days", this is, the lead time from customer order to customer delivery is about ten days. This difference in lead times induces the establishment of strategic safety stocks in different echelons of the SC (Forster et al., 2013).
6. <u>Planning Horizons</u> – The difference in lead times induces different planning horizons. In general, due to the long lead time, the semiconductor industry works with long-term plans, up to six months. On contrary, the automotive industry operates with short-term plans, following the JIT and JIS production systems. As a result, the automotive industry is more flexible and adaptable since can change horizon plans rapidly (Forster et al., 2013).
7. <u>Production Flexibility</u> – In general, the semiconductor industry has very low flexibility since it works with full capacity, following a 24/7 production plan. In this way, it is very difficult to change the production plan and accept extra orders. The automotive industry is much more flexible, being able to add resources and change the production plan quite easily, in order to meet unforeseen demand that arises (Forster et al., 2013).

As was possible to acknowledge, semiconductor and automotive industries have very different SC characteristics, that jeopardize the stability of the market and poses extra challenges to companies.

4.3 Supply Chain Risk Management (SCRM)

Due to globalization, e-commerce and the environment and trends volatility, SC are becoming more and more complex, interdependent and exposed to SCRs (Shekarian & Mellat Parast, 2021). As a result, avoiding and mitigating the impact of disruptions and limiting the ripple effect is more and more challenging (Bier et al., 2020). To do this, SCRM plays a critical role since this methodology helps to identify, assess, mitigate and monitor the risks that can be the source of a disruption and contributes to fostering SCRES and robustness (el Baz & Ruel, 2021). According to Blos et al. (2009), SCRM has emerged as a promising research field, resulting from the interception between SCM and RM. The main objective of SCRM is to create the capability to diminish SC vulnerability and to guarantee business continuity and performance. According to Fan & Stevenson (2018), SCRM can help a company to differentiate itself from the competition because a company that can manage the risks can improve its market position. In this way, SCRM also fosters profitability and can contribute to sustainable growth.

Although SCRM is a widely discussed research topic, a unique definition that is accepted by the whole scientific community does not exist. Thus, as it is possible to visualize in Table B. 2, Appendix B, several authors have presented different definitions of SCRM. In 2006, Tang (2006) published a comprehensive paper, where he defined SCRM as "the management of supply chain risks through coordination or collaboration among the supply chain partners so as to ensure profitability and continuity". Later, in 2015, Ho et al. (2015) also proposed his definition of SCRM as a collaborative effort, made between organizations through qualitative and quantitative risk approaches to identify, assess, mitigate and monitor the risk events that could negatively affect some part of the SC. In the same year, Aqlan & Lam (2015) proposed a SCRM definition that reinforces the concept of disruption, characterizing SCRM as a systematic methodology, whose main goal is reducing the impact of disruptions in SC.

SCRM has been attracting more and more researchers and practitioners because it offers great potential to reduce the impact of disruptions in SC operations (Yang et al., 2021). As a result, the stages of the SCRM process also have been extensively studied in the literature. However, like the definition of SCRM, there is no consensus regarding the number and denomination of the stages that form the SCRM process. Ho et al. (2015) proposed a SCRM process that encompassed risk identification, risk assessment, risk mitigation and risk monitoring. Aqlan & Lam (2015) proposed a SCRM process formed by risk identification, risk evaluation, risk mitigation and risk monitoring. In this literature review, the SCRM process proposed by Fan & Stevenson (2018) and later applied by Louis & Pagell (2019) is going to be adopted because it is considered more comprehensive. This SCRM process is composed of 4 stages, described next: risk identification; risk assessment; risk treatment; and risk monitoring. Figure 11 sums up these 4 stages and the steps that are going to be analysed in each stage.

Figure 11 - SCRM process. Source: João Azinhais

4.3.1 Supply Chain Risk Identification (SCRI)

SCRI is the first nuclear stage of every SCRM process because it helps to identify and classify risks, which is critical to trigger the subsequent phases (Kleindorfer & Saad, 2005). In this way, risk identification concentrates on the permanent scanning of new possible threats and risks that impact the SC (Kern et al., 2012). This first stage plays a crucial role in the SCRM process because directly influences the next stages since only risks identified can be later assessed, treated and monitored (Fan & Stevenson, 2018). According to these authors, every risk identification should have two steps: risk listing and classification. The first step consists of enumerating all the risks observed while the second comprises the risk categorization into a group, commonly called risk type. Louis & Pagell (2019) presented a more holistic view of SCRI, defining it as the process of finding, understanding, defining and classifying SC risks and warning indicators. These two authors present a comprehensive study in SCRI, especially risk categorization, because, according to their view, SCRI is the less studied stage of SCRM and exists a research gap that is urged to be explored. Several tools and techniques have been used to identify SC risks, such as brainstorming, semi-structure interviews, flowcharts, Ishikawa Diagrams, cause and effect diagrams and fault trees. Indeed, semi-structured interviews are an increasingly used method in studies related to SCDs, SCRM and SCRES to identify the main risks and threats that a company faces. Some examples of the application of semi-structured interviews in the literature are:

- Leat & Revoredo-Giha (2013) studied a pork SC with the purpose of identifying risks and challenges in building a resilient SC. To do this, the authors carried out semi-structured interviews with senior SC managers to gain information about the key risks and concerns faced on the production and supply sides and possible responses to deal with those risks.
- Shareef et al. (2020) studied the SC operations during disaster scenarios in Bangladesh and the impact of disruption risks. In this study, 500 interviews with different stakeholders were conducted to identify and categorize several disruption risks.
- Islam et al. (2021) performed semi-structured interviews in focus groups to obtain information concerning vulnerabilities, that can cause a hypothetical disruption of the coastal maritime transport System of Vancouver, and the strategies that could be applied to deal with that risk.
- Prakash (2022) studied a dairy products' SC in India to identify the sources of SCD that are affecting SCRES. This author also used a semi-structured interview protocol to perform 28 interviews with dairy organizations with the goal of identifying the risks that originated from disruptions.

However, according to Fan & Stevenson (2018), researchers and practitioners are not on the same page regarding SCRI methods because, while the first ones seek to focus on complex approaches, such as analytical hierarchy process (AHP), the second ones focus on established methods such as value stream maps (VSMs) or Ishikawa Diagrams. Moreover, some decision support tool has been also developed. For instance, Sachdeva et al. (2012) presented a new decision support tool called Supply Chain Risk Identification System (SCRIS), whose main goal is to assist decision-makers in the process of SCRI and in understanding the interrelationships between risks within the SC network. This tool uses a knowledge-based system approach and considers different process strategies like make-to-order (MTO), make-to-stock (MTS) or engineering-to-order (ETO).

SCR definition and classification

According to Ho et al. (2015), SCR incorporates the likelihood and impact of an anticipated risk event that negatively influences any entity of the SC at strategic, tactical or operational levels. Louis & Pagell (2019) presented a different definition, defining it as the undesirable negative deviation from expected outcomes that influence SC operations and impact firm performance. Concerning SCR types, several classifications have been proposed, as established in Table B. 3, Appendix B. Christopher & Peck (2004) divided risk into three major categories: internal to the firm; external to the firm but internal to the SC network; and external to the network. The first category comprises process and control risks while the second includes demand and supply risks, and the third is formed by environmental risks. Tang (2006) divided risks into operational and disruption. Thus, operational risks are related to uncertainties originated within the SC, like supply, demand or cost uncertainties whilst disruption risks are caused by natural or man-made disasters. This author also underlined that, in the majority of cases, the impact of disruption risks in companies is much higher than that of the operational risks. Wagner & Bode (2008) considered five groups of SCRs: demand; supply; regulatory, legal and bureaucratic; infrastructure and catastrophic. The author reinforced that the first two are associated with supply-demand coordination within the SC, while the others deal with risk sources that can be external to the SC. Ho et al. (2015) divided SCR into two categories: macro-risks and micro-risks. On the one hand, macro-risks are related to rare and extreme events, that are unlikely, but that cause huge damage to SC when they occur, such as natural disasters, war, or terrorism. On the other hand, micro-risks are related to usual events, instigated by internal processes of the company or interactions within entities, that can compromise the entire SC. Micro-risks can also be divided into four subgroups: supply risk, demand risk, manufacturing risk and infrastructure risk, being this last one formed by information, financial and transportation systems.

In the previous classifications of risk types, the disruption risk is either considered a specific type of risk, as was proposed by Tang (2006), or a risk correlated with the other types, as it happens in the majority of classifications. Dolgui et al. (2020) defined a disruption risk as a "low-probability-high-impact" risk, distinguishing it from operational risks, such as, demand fluctuations, that are considered "high-probability-low-impact risks", as established in Figure 12. Disruption risks are associated with the ripple effect while operational risks are related to the bullwhip effect.

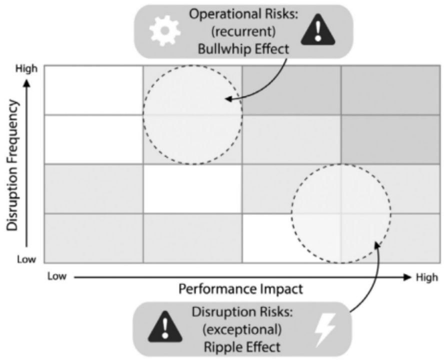

Figure 12 - Operational vs Disruption risks. Source: Extracted from (Dolgui et al., 2018)

4.3.2 Supply Chain Risk Assessment (SCRA)

SCRA the second stage of every SCRM process and, according to the majority of researchers, has the main goal of analysing and evaluating each risk in detail, namely, its likelihood of occurrence and the impact that it can generate (Kern et al., 2012). According to these authors, this stage is responsible for analysing in depth the potential triggers, causes and effects of the risks previously identified, that occurred inside an organization or along with its network, through the data collected. However, as managing risks is a process that requires a substantial investment, companies cannot deal with all risks with the same urgency (Fan & Stevenson, 2018). Therefore, it is essential to perform a SCR prioritization, in order to define a sequence to treat risks, giving importance to the major ones, which usually are those that cause a great impact on a firm´s performance and/or have a large probability of occurrence. In this way, this step helps companies to manage their limited risk resources and budget (Zsidisin, 2003). In the risk assessment stage, the interrelationships between risks should be also analysed because, in general, a risk is not an out-of-the-way occurrence. Indeed, risks use to present several interrelationships with other risks and phenomena and might affect all SC (Sachdeva et al., 2012). Sarker et al. (2016) identified two main types of dependencies that arise from the management of risks in business silos: positive dependence, when a risk elimination leads to other risk removals, and negative dependence, when a risk deletion generates other risks.

Several methods have been developed in the stage of SCRA. According to Sarker (2019), some of the most relevant risk assessment methods are: the risk matrix, the AHP, scenario analysis or different types of failure mode and effect analysis (FMEA). The most used method, both by researchers and company practitioners, is considered to be the probability-impact risk matrix (Fan & Stevenson, 2018). In 2021, Hermoso-Orzáez & Garzón-Moreno (2021) combined the AHP model, to hierarchize the risks according to their relevance, with the probability-impact matrix in the risk assessment stage, which allow them to mix quantitative and qualitative analysis. Ghadir et al. (2022) proposed a modified FMEA, that includes the Best-Worst Method to overcome the disadvantages of the traditional FMEA, to evaluate the impacts of the COVID-19 pandemic on SCRs. The study was applied to an automotive spare part company in Iran and contributed to identify the ten major SCRs during the COVID-19 outbreak. Furthermore, Bayesian networks (BN) are considered to be a relatively new and promising method to model SCRs and SCRES. Hosseini & Ivanov (2020) developed a comprehensive paper, whose results showed that the application of BNs to the field of SCRM and resilience is a powerful area of interest for both researchers and practitioners, because it can capture the interrelationships between risk sources, consequences and treatment strategies. Qazi et al. (2022) combined BNs with Monte Carlo simulation to model SCRs and capture the Risk Network Value at Risk (RNVaR), which is defined as "the maximum risk exposure expected at a given confidence level for a given time frame, associated with individual SC performance measures within a network setting". This study was applied to the telecommunication sector and introduced new risk metrics to determine the impact caused by individual risks over several performance indicators.

4.3.3 Supply Chain Risk Treatment (SCRT)

After performing the SCRA stage, it is indispensable to decide which kind of strategy should be adopted to deal with the risks identified and evaluated. It is common to call this stage risk mitigation. Nevertheless, risk mitigation is only one of the possible strategies to treat risks. In this literature review, the vision of Fan & Stevenson (2018) is going to be adopted, who defended that there are five types of risk treatment strategies: acceptance, avoidance, transfer, sharing and mitigation.

Risk Acceptance

The first strategy, risk acceptance, should be followed when a given risk has a low probability of occurrence and low impact, and/or the cost of avoiding/transferring/mitigating the risk is considerably higher than its projected benefit (Aqlan & Lam, 2015). However, it could be difficult to establish the threshold beyond which the risk should not be accepted. This may depend on the company´s context and is usually correlated with the company´s risk propensity and profile, i.e., the willingness that the organization presents to deal with risk and to accept possible negative outcomes (Park et al., 2016).

Risk Avoidance

Risk avoidance has the objective of eliminating the root causes and trigger events that originate the risk (Aqlan & Lam, 2015) and this might include replanning the operations and redesigning the whole SC (Deshmukh, 2007). This kind of treatment is done when risks have a great probability of occurrence and a high estimated impact and so this transformation can offset the investment made because, if the risks are not avoided, they could undermine the survival of the business.

Risk Transfer

Risk transfer means that the risk is assigned to another party. It can be done, for instance, through an insurance company, where the insurance company takes the risk of other organization for a given price (Diabat et al., 2012). Indeed, a business interruption insurance can be used to transfer business disruption risks, protecting the organizational income and helping the firm to restart its normal operation (Zhen et al., 2016). According to Aqlan & Lam (2015), this type of strategy is more suitable for some disruption risks, such as natural disasters or terrorist attacks, where the impact is higher but the probability of occurrence lower than for operational risks.

Risk Sharing

Risk sharing occurs when some risks are shared with other parties and, as risk transfer, is suitable for dealing with risks with a low probability of occurrence and a high expected impact (Fan & Stevenson, 2018). This type of treatment is used when SC partners consider that is more convenient for both to share the risks of a certain activity or operation. Shanker & Satir (2021) showed that a risk sharing contract gives, even to a buyer and supplier located in different countries, a considerable enhancement in the total expected utility, being the contract beneficial for both parties.

Risk Mitigation

Risk mitigation is, definitely, one of the most studied steps of the SCRM process and intends to diminish the probability of occurrence of a given risk and/or to reduce its potential impact (Parast & Shekarian, 2019). It includes a set of countermeasures that can be applied before or after the disruption occurs (el Baz & Ruel, 2021). In this way, risk mitigation encompasses two distinct main types of strategies: proactive and reactive. Proactive strategies are implemented to reduce the probability of a given risk before the disruption occurs while reactive strategies are used to diminish the negative impact that arises after a disruption (Kırılmaz & Erol, 2017). The first strategies are also called mitigation tactics and are done in advance of a disruption and the second ones are also named contingency tactics because they include contingency plans, elaborated to respond to a disruption (Matsuo, 2015). According to Ivanov et al. (2017) proactive strategies create protections and prevent possible perturbations without considering recovery measures while reactive strategies have the goal of adjusting processes and structures when facing unforeseen occurrences.

Regarding proactive strategies, several options have been studied. According to Sheffi & Rice (2005), the resilience of a SC towards the mitigation of a disruption can be accomplished by investing in redundancy and flexibility. On the one hand, redundancy can be achieved through: safety stocks; multiple suppliers (even knowing that secondary suppliers have higher costs); and low-capacity utilization rates. On the other hand, the authors pointed out that flexibility can be potentially obtained at five elements of a SC: supply and procurement; conversion processes; distribution channels; control systems and corporate culture. Hendricks & Singhal (2011) considered that flexibility can be enhanced in three fields: flexibility in the product design (where standardization, modularity and the use of common parts should be considered as preventive strategies); flexibility in sourcing (achieved through flexible contracts with suppliers and spot markets to buy parts and supplies) and flexibility on manufacturing (achieved through flexible capacity, needed to deal with a volatile demand or a disruption). Moreover, Knemeyer et al. (2009) addressed the proactive process of planning for catastrophic events, considering that expanding the existing inventory and distribution facilities as well as moving SC facilities away from high-risk locations should be considered proactive countermeasures. Grötsch et al. (2013) explored the antecedents of proactive SCRM and concluded that it is crucial that managers applied risk management systems in enterprises because they are the most efficient way of transferring risk legal requirements into effective management actions. Torabi et al. (2015) studied the fortification of suppliers, suppliers' business continuity plans and contracts with backup suppliers as proactive strategies to improve the resilience of the suppliers' network. More recently, Baryannis et al. (2019) highlighted the importance that Artificial Intelligence algorithms might have in proactive strategies, namely helping with the accurate estimation of the probability of occurrence and the potential impact of risks. However, in spite of being a promising topic, more efforts should be employed in its research. The application of proactive strategies in an effective way requires an awareness of different stakeholders, namely decision makers, that should be able to forecast market fluctuations, in order to incorporate these changes into proactive planning (Wieland & Wallenburg, 2013).

Concerning reactive strategies, several studies have been also made. On the one hand, it is important to have contingency plans, which are a set of countermeasures prepared in advance, but applied after a potential risk event occurs (Hopp et al., 2011). According to these authors, a contingency plan should include several steps: a) identify potential backup suppliers, in order to have alternatives when the disruption occurs; b) make flexible contracts with suppliers, with clauses that forced the suppliers to deliver quantities above the normal in a specific period, after a disruption.

This guarantees that non-disruptive suppliers cover at least some part of the disrupted ones; c) take into account flexibility in the design stage, in order to create more flexible products, that accept different components; d) promote process and organizational flexibility. Furthermore, other contingency tactics have been studied. Tomlin (2006) considered that rerouting and demand management can be also applied as contingency measures. Nevertheless, the first one is a plausible solution only if suppliers have some flexibility to increase their capacity and the second one should be taken into account customer preferences. Ivanov et al. (2017) also considered four types of redundancy as recovery strategies: backup suppliers; backup depots and transportation channels; inventory and capacity buffers, and capacity expansion. However, having a good contingency plan is not enough. After a disruption occurs, it is important to create a crisis management plan, with a set of measures, namely: a) recognize that a disruption has occurred and develop a response; b) create a disruption management team, formed by members of different affected stakeholders, and ensure that the communication is effective; c) build an initial plan to respond quickly to the problems; d) update the plan as new information emerges; and e) do a lessons learned evaluation, to incorporate effective measures into future disruptions (Hopp et al., 2011). A paradigmatic example of a good crisis management process was given by the company Ericsson after the Tohoku Earthquake in 2011 and the subsequent tsunami and nuclear disaster. On March 13, 2011, at 6:46 CET, an 8.9 magnitude seism devastated the coast of Japan, affecting several global semiconductor SCs in the world. To respond to this potentially devastating disruption, Ericsson activated immediately its Ericsson Supply Chain Management Task Force and a meeting between several stakeholders occurred two hours after the earthquake (09:00 CET). In that meeting, Ericsson: analysed the suppliers and sub-suppliers in the affected geographical area; examined manufacturing facilities in the area; scrutinised the possibility of a SCD and the financial impact that it could generate; contacted Japanese suppliers to assess the extension of the damages and searched for back-up suppliers. This initial approach has shown the effectiveness of Ericsson´s SCRM process (Norrman & Wieland, 2020).

Nevertheless, an organization is not restricted to one single strategy, being crucial to have a good equilibrium between proactive and reactive strategies (Tomlin, 2006) because, in many cases, is this mix of approaches that allows companies to treat properly disruption risks (Norrman & Wieland, 2020). Kilubi (2016) proposed a comprehensive SCRM framework that distinguishes, on the one hand, *ante-disruption* and *post-disruption* states, and, on the other hand, *proactive* and *reactive* strategies. In this way, this author compiled different proactive and reactive strategies mentioned in the literature and assign each one to a specific type of SC (I to IV), considering, as well, the type of risk (supply vs demand risks). As it is possible to see in Figure 13, a company that faces high exposition to supply risks but low to demand risks, should follow a proactive strategy focused on coordination, redundancy, visibility and transparency. This is what happens in the case of the automotive SCs regarding the supply of semiconductors nowadays because car companies face a relatively stable demand but are highly exposed to shortages of chips.

Figure 13 - SCRM strategies framework. Source: Extracted from Kilubi, 2016

4.3.4 Supply Chain Risk Monitoring

Risk monitoring is the last stage of the SCRM process and, perhaps, the least studied in the literature, which requires more focused research, especially regarding the tools needed to monitor and control risks (Blackhurst et al., 2008). The objective of risk monitoring is to continuously assess how risk factors and sources are evolving, in order to evaluate the effectiveness of the treatment strategies applied (Fan & Stevenson, 2018). Therefore, this process requires uninterrupted attention, so as managers are aware of changes and able to incorporate new information into the process, updating it and reviewing the decisions made. (Zsidisin, 2003). According to Norrman & Wieland (2020), risk monitoring not only fosters the implementation of new actions and changes, but also creates a learning platform for analysis and reflections, and so, urges deeper investigations.

4.4 ISO 31000 – Risk Management

One alternative to the SCRM process previously described is the application of the international standard *ISO 31000*, proposed by the International Standard Organization (ISO) in 2009 and updated in 2018. *ISO 31000* has the main objective of providing organizations with a set of guidelines that helps them in the development of risk management strategies to effectively identify and mitigate risks (International Standard Organization, 2018). As the SCRM process, *ISO 31000* also has its own process, formed by 2 main stages: risk assessment; and risk treatment. Risk assessment is composed of risk identification, risk analysis and risk evaluation (International Standard Organization, 2018). Overall, the SCRM process and *ISO 31000* have several similarities. However, scientific studies that apply *ISO 31000* to the field of SCRM are considerably scarce in the literature. One of the only exceptions is the work of de Oliveira et al. (2017), who "inferred that *ISO 31000* can be used beneficially as a standardized method to perform SCRM, as long as tools and techniques are selected according to the company needs and business characteristics". In this way, it is important to deepen the knowledge related to *ISO 31000*, especially focusing on the application of this standard to the SCM field.

4.5 Supply Chain Resilience (SCRES)

4.5.1 Definition and relevance

Nowadays, SCs are constantly exposed to new risks and threats, that arose due to globalization and the increase of complexity and interdependence between the echelons that constitute the SCs. Therefore, as was previously mentioned, the probability of having a major disruption that compromises the sustainability of a business has also been raising. In this context, the concept of SCRES has emerged. Although it has been studied by many researchers, the concept of SCRES is still not well established in the literature and remains a discussion topic in the work of several researchers (Ribeiro & Barbosa-Póvoa, 2022). One of the most well-known definitions was proposed by Ponomarov & Holcomb (2009), who stated that SCRES encompasses not only the adaptative capacity of a SC to be prepared for unforeseen occurrences but also the ability to respond to disruptions and recover from them while guaranteeing the continuity of operations and the control over structure and function. More recently, Ribeiro & Barbosa-Povoa (2018) proposed a new simple and objective, but also comprehensive, definition of resilience that stated that "a resilient SC should be able to prepare, respond and recover from disturbances and afterwards maintain a positive steady state operation in an acceptable cost and time". This definition emerged from a new framework developed by the authors that includes four pillars, essential to building a SCRES definition, which are: focus event; performance level; speed; and adaptative framing. However, despite the lack of consensus regarding its definition, researchers tend to agree that SCRES can create a sustainable competitive advantage, not only at strategic but also at operational levels, being indispensable to organizational success (Hamel & Välikangas, 2003; Sawyerr & Harrison, 2020). Indeed, the COVID-19 pandemic, as one of the major disruptions in history, also showed the importance of having resilient SCs even for the survival of a business. According to Remko (2020), the COVID-19 pandemic can be an opportunity to bridge the existent gaps between practitioners and researchers regarding resilience since resilience is now, more than ever, a critical area of focus for SC managers, who seek to improve their capabilities in disruption management.

4.5.2 Relationship between SCRES and SCRM

As was possible to acknowledge during this literature review, the concepts of SCRES and SCRM are interconnected and are critical when a SC faces a disruption. The relationship between these two concepts has been studied by several researchers. According to Heckmann et al. (2015) the concepts of SCRES and SC vulnerability emerged from the concept of SCR, being SCR a primary concept and SCRES and vulnerability derived concepts. In this way, the authors defined SC vulnerability as "the extent to which a SC is susceptible to a specific or unspecific risk and SCRES as the ability of a SC to overcome vulnerability". Some authors defended that SCRES might fill some gaps of SCRM such as the difficulty of getting the probability of occurrence of a low-probability-high-impact risk during the assessment stage (Pettit et al., 2010). Nevertheless, is quite consensual that SCRES, as a descendant of SCRM, cannot be achieved separately, without involving the ideas and knowledge driven by SCRM (Pereira et al., 2014). In this way, SCRES should be positively influenced by SCRM (Jüttner & Maklan, 2011). Furthermore, with the high increase in complexity, current SCs are constituted by numerous echelons, more and more interconnected and interdependent, that should work to build solid partnerships that allow sharing not only benefits but also risks (Ribeiro & Barbosa-Povoa, 2018). To develop this policy of risk sharing, companies must be aware of their risk exposure and ought to be able to manage risk holistically and comprehensively through the SCRM process (Ponomarov & Holcomb, 2009).

4.5.3 SCRES components

Like the concept of SCRES, the components that constitute this field of research remains in discussion since several concepts were proposed by researchers and the scientific community has not achieved a consensus yet. Christopher & Peck (2004) defended that in order to create a resilient SC four principles are indispensable: SC (re)engineering; SC collaboration; agility; and creating a SCRM culture. Then, Jüttner & Maklan (2011) considered that SCRES is formed by four capabilities (flexibility, velocity, visibility and collaboration), which are essential to avoid or limit the negative impact of a risk event. Wieland & Wallenburg, (2013) advocated that SCRES encompasses two mechanisms: robustness and agility. On the one hand, to obtain robustness, a company must have anticipation and preparedness, so as to forecast future changes and be ready when they happened, respectively. On the other hand, to achieve agility, a firm must be able to identify current changes and act fast to react when they happen, this is, a firm must have visibility and speed. Therefore, while robustness is the proactive dimension of resilience, agility is the reactive dimension. Juan et al. (2022), mixing the ideas of several researchers, explored the concept of SCRES as being formed by five components, that are going to be analysed hereafter: visibility; velocity; flexibility; robustness; and collaboration.

Visibility

SC visibility implies access to high-quality information that describes the intrinsic characteristics of demand and supply. To be considered of high quality, it must be accurate, timely, comprehensive and useful and should be provided by several sources (Williams et al., 2013). SC visibility encompasses not only internal visibility, with effective communication systems inside the organization, but also the availability of access to upstream and downstream inventories, as well as production and purchasing schedules (Christopher & Peck, 2004). SC visibility is also considered an effective SCRM strategy that can be applied both proactively and reactively, as is established in Figure 13 (Kilubi, 2016).

Velocity

SC velocity, also known as speed, is crucial to build an agile SC and should be based on three pillars: streamlined processes; decrease inbound lead-times; and reduce non-value-added time (Christopher & Peck, 2004). This concept is essential when facing a disruption because, the higher the response time to a disruption, the higher the risk exposure of a firm and the higher will be the impact of a disruption on SC performance (Azadeh et al., 2014).

Flexibility

SC flexibility is the ability of SC actors to adapt or respond to unforeseen events, as well as satisfy customer demand requirements without compromising the sustainability of the business in terms of money, costs, organizational order and performance (Manders et al., 2016). The enhancement of flexibility in the application of mitigation and contingency plans is also critical to reduce the risk exposure to a disruption and diminish the negative consequences generated by a disruption, respectively (Skipper & Hanna, 2009). In this way, SC flexibility, either through the application of a flexible network design or the creation of flexible contingency plans and production schedules, contributes to boost SCRES since has an important role in preparing, responding and recovering from disruptions (Piprani et al., 2022).

Robustness

Robustness is the capability of a SC to resist changes without modifying its original stable configuration and one of the mechanisms of SCRES (Wieland & Wallenburg, 2013). While the former authors considered that anticipation and preparedness are the requirements to build robustness, Mackay et al. (2020) defended that robustness consists in an absorptive capacity that requires resistance and avoidance, as dimensions. Nevertheless, both groups of researchers agree that robustness is a critical component to respond to disruption and to build SCRES.

Collaboration

SC collaboration arises from the sharing of resources and capabilities between SC partners, such as communication and technology systems or financial resources, and it is influenced by a range of factors, including the organizational structure and culture, the flexibility and visibility of the company or the stakeholders (Duong & Chong, 2020). The establishment of a SC collaboration culture that allows the exchange of information between SC actors is also considered a key priority for SCR reduction (Christopher & Peck, 2004).

4.6 Chapter conclusions

As acknowledged during this literature review, the concepts of SCD, SCRM and SCRES are interconnected. Nowadays, as SCs are becoming more and more complex, interdependent and exposed to SCRs (Shekarian & Mellat Parast, 2021), the SCRM process plays a critical role since this methodology helps to identify, assess, mitigate and monitor the SCRs that can be the source of a SCD and contributes to fostering SCRES and robustness (el Baz & Ruel, 2021). Thus, this process is going to be applied as the main methodology of this master thesis following the comprehensive paper of Fan & Stevenson (2018). In addition, this thesis intends to bridge the existent gap presented by Ho et al. (2015), who stated that the majority of works in the literature that apply the SCRM process are theoretical in nature and have not been validated empirically. This author referred that scholars should investigate the applicability of SCRM models in practical situations. Therefore, this thesis intends to apply the SCRM process to a real automotive company, VW AE, to cope with the semiconductor disruption in the automotive industry, contributing to overcoming this research gap. Moreover, Louis & Pagell (2019) stated that SCRI is the less studied stage of SCRM and exists a research gap that is urged to be explored. The thesis intends to contribute to this research gap by developing a new holistic risk categorization. This study will also contribute to the need of studying systemic disruptions, identified by Ramani et al. (2022), since researchers tend to focus on disruptions that have an individual or local impact, instead of systemic disruptions, like the semiconductor crisis, which has a global impact in several industries. Therefore, as the focus of this thesis is placed on studying the systemic semiconductor disruption faced by the automotive industry, it will contribute to enriching the study of systemic disruptions. Regarding the SCRA stage, the developed model will be based, mainly, on the paper of Hosseini & Ivanov (2020), who showed that the application of BNs to the field of SCRM and resilience is a powerful area of interest for both researchers and practitioners, being a promising area that needs to be explored. Thus, this work will also contribute to this new research hotspot on SCM, with an application of a BN to a real automotive company.

5 Methodology and Discussion

As stated in the literature review chapter, SCs are becoming more and more complex, interdependent and exposed to SCRs (Shekarian & Mellat Parast, 2021). VW AE´s SC is no exception. The semiconductor crisis that disrupted worldwide automotive SCs has also been affecting VW AE's operations, as pointed out in section 3.2.6. This crisis has severely affected the capacity of first-tier suppliers in delivering the subsystems and, as a result, the risk of failing a delivery exists, which can affect VW AE's production, lead times and even the ability to satisfy the demand. Therefore, it is critical to study VW AE's SC, with especial focus on the threats and risks that can jeopardize the company's performance. To do this, the SCRM process plays a crucial role since this methodology helps to identify, assess, treat and monitor the risks that can be the source of a SCD and contributes to fostering SCRES and robustness (el Baz & Ruel, 2021). The international standard *ISO 31000* might be used as a systematic procedure for studying SCRM. However, since the application of *ISO 31000* to study SCRs has received little attention in the literature, it is not going to be considered as a methodology. Thus, the SCRM process is going to be the main methodology used in this study. As in section 4.3., where the SCRM process proposed by Fan & Stevenson (2018) was followed to conduct the SCRM review, in the methodology chapter the process proposed by these authors is also going to be adopted. This SCRM process is composed of four stages: 1) risk identification; 2) risk assessment; 3) risk treatment; and 4) risk monitoring. Figure 14 sums up the stages of the methodology, as well as the steps and the data source used in each stage.

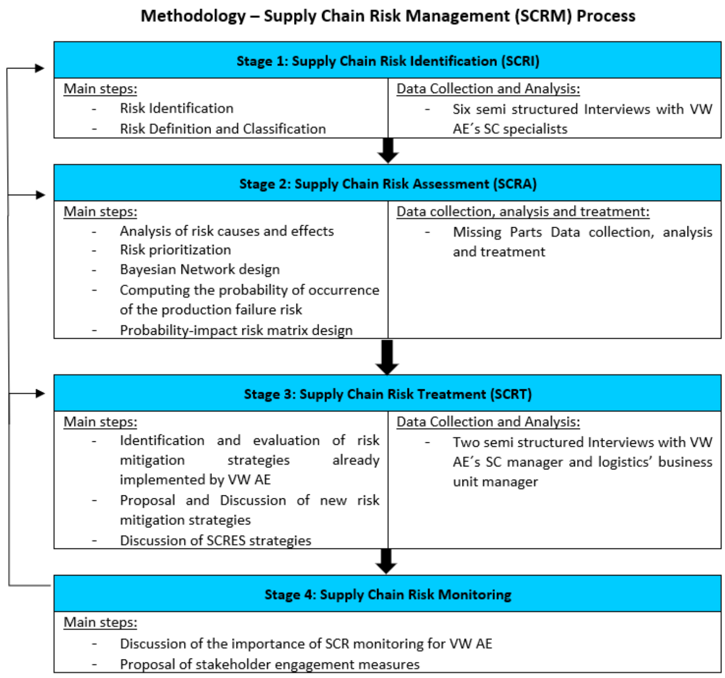

Figure 14 - Methodology applied in this study. Source: João Azinhais

In the risk identification stage, the main risks that exist in VW AE's SC are going to be identified through a set of six semi-structured interviews with SC specialists. After being identified, the risks will be defined and classified, according to two existing and one proposed classifications. Then, the risk assessment stage starts with the analysis of risk causes and effects. A risk prioritization is also performed in order to select the risks that have a major impact on VW AE´s operations, since only these will be deeply analysed. The risk prioritization will be fed by the interview conducted with the SC manager, where she was requested to classify the impact of the identified SCRs on a qualitative scale of 1 to 5, being 1 the least impact and 5 the highest impact that a risk can produce in VW AE. With the risk prioritization, it was decided to continue studying the supply failure risk and the production failure risk. The analysis of these risks will start with the design of a BN that represents VW AE's plant and first-tier suppliers, in order to obtain the probability of occurring a production failure in VW AE considering the probability of existing a supply failure. In this step, missing parts data will be analysed and treated, and the conditional probability theory will be used to compute the referred probabilities. Then, after computing the probability of occurring a production failure in VW AE and considering the impact of this risk, a probability-impact risk matrix will be built. In the SCRT stage, risk mitigation strategies will be analysed, considering two semi-structured interviews conducted with VW AE´s managers. This stage will encompass the analysis of mitigation strategies already implemented by VW AE and others proposed by this study, as well as strategies to foster SCRES in VW AE's SC. The methodology chapter will end with a brief discussion of the importance of SCR monitoring to VW AE and a proposal of stakeholder engagement measures.

5.1 Supply Chain Risk Identification (SCRI)

As was possible to acknowledge in the literature review chapter, SCRI is the first phase of every SCRM process and it plays a critical role because it triggers the following stages of the process (Kleindorfer & Saad, 2005), as only risks that are identified can be afterwards assessed, treated and monitored (Fan & Stevenson, 2018). However, despite being the first step in the process, SCRI has received little attention in the literature, remaining a research gap (Louis & Pagell, 2019). A point that, to the best of my knowledge, has not been studied, remaining also a research avenue, is the importance of SC workers, namely managers, in SCRI. Indeed, this stage of the process requires dedication and good screening capabilities of SC workers, that must be able to analyse their organizations not only internally, but also externally. Firstly, they must be aware of teams' weaknesses, in order to identify potential threats that can arise inside the organization. Then, they should be able to analyse the network of stakeholders directly involved in their operation so as to identify possible conflictive objectives between the parts, that can endanger the companies' success. Finally, they must be capable of analysing their surroundings, to be aware of market trends and patterns that can originate relevant risks which, if not analysed, can jeopardize the business. Therefore, although SC managers can delegate the SCRI stage to other SC workers, the supervision of managers is important because, in general, they are more aware of potential risks and threats.

Several methods can be applied to identify SCRs such as brainstorming, Ishikawa Diagrams or semi-structure interviews (Fan & Stevenson, 2018). In this study, the semi-structured interview was chosen as the method to collect information regarding the risks that are affecting the semiconductor SC of VW AE. Firstly, this method was chosen because it is widely used in the literature in studies related to SCDs, SCRM and SCRES to identify the main risks and threats that a company faces, as explained in section 4.3.1.

In total, six oral interviews were performed during July 2022, in VW AE's installations, where the interviewees work. The interviewees were carefully selected, considering their responsibilities and experience in the automotive industry and the SCM field. In this way, one SC planner, four SC coordinators and one SC manager of VW AE's SC were selected. This selection was made to encompass several organizational hierarchy levels, in order to obtain different perspectives and to enrich data collection. Besides, the SC manager of VW AE was included in this data collection to answer to the research avenue previously stated, related to the importance of involving SC managers in the SCRI stage. All interviewees agreed to record the interview, which allowed the collection of all information, being this procedure considered the most accurate interview documentation technique (Spieske, et al., 2022; Yin, 2014). Moreover, handwritten notes were also taken during the interview to sum up the most important topics. It was developed an interview questionnaire to guide the interview and ensure the reliability and comparability of responses (Yin, 2014). This interview protocol, which can be consulted in section C1 (appendix C), was based on a comprehensive literature review on disruption management, SCRM and SCRES.

The collected data was later analysed in a series of steps. Firstly, audio recordings were listened and carefully transcribed and handwritten notes were examined. Afterwards, the transcribed interviews were shared with interviewees for final validation and some clarification, if needed (Yin, 2014). Then, data was organized and labelled into big topics, each encompassing common or related information. Finally, the data was filtered in order to obtain only the most relevant information.

The first part of the interview questionnaire included information regarding the interviewee' data, namely the role in VW AE and the experience in the automotive industry and in SCM, which can be consulted in Table 5. Then, questions regarding the semiconductor disruption in the automotive industry were asked, namely related to the risks that were affecting VW AE's SC. Several common risks were presented, taking into account the literature review performed, and others were pointed out by the interviewees. Different categories of risks, such as supply-side risks or disaster risks were asked. All the risks were then discussed. In the interview with the SC manager was requested to classify the impact of the identified SCRs on a qualitative scale of 1 to 5, being 1 the least impact and 5 the highest impact that a risk can produce, in order to perform the risk prioritization in the SCRA stage. Moreover, other questions regarding the management process of risks were also asked, to know how VW AE identifies risks and threats in its SC, who is responsible for that and what importance the company gives to this process.

Table 5 - Interviewee' data and experience

Person	Role/Responsibility	Years in the automotive Industry	Years in SCM
1	SC planner	10	7
2	SC coordinator	30	12
3	SC coordinator	32	4
4	SC coordinator	28	23
5	SC coordinator	33	28
6	SC Manager	23	15

SCRI – Definition, list and classification

During the semiconductor crisis induced by the COVID-19 pandemic (Ramani et al., 2022), the automotive industry in general, and the VW AE's SC in particular, has been facing several risks. In this work, a SCR is every factor or threat, with a specific likelihood of occurrence, that could produce a negative impact on VW AE's SC. With the performed interviews, it was possible to identify several SCRs that affect VW AE's SC:

1. SC disruption;
2. Supply failure;
3. Supplier delay;
4. Lack of supplier capacity;
5. Delay in transporting supplies;
6. Production failure;
7. Incapacity of satisfying car demand within normal lead time.

These SC risks, as well as their causes and effects, are going to be deeply analysed in section 5.2.1.

In terms of risk types, several classifications can be adopted, as stated in section 4.3.1 and in Table B. 3 (Appendix B). Hereafter, are going to be analysed the classifications proposed by Wagner & Bode (2008) and Ho et al. (2015) since are considered to be the most comprehensive:

- According to Wagner & Bode (2008), five of the identified risks (SC disruption risk; supply failure; supplier delay; lack of supplier capacity and delay in transporting supplies and production disruption) would be classified as supply risks because they are associated with the upstream side of the SC. Even the first risk, that is the risk of disrupting the whole SC would have to be classified as a supply risk since the category that this author identified as a *catastrophic risk* only includes events such as epidemics, natural disasters, wars or terrorism. Therefore, systemic disruptions that affected the whole market/industry, like the one that affected the automotive industry due to the semiconductor crisis (Ramani et al., 2022), cannot be classified as a consequence of this *catastrophic risk.* The sixth risk, associated with the failure in a production facility, is not addressed in this classification proposed by Wagner & Bode (2008). The last risk (incapacity of satisfying car demand within normal lead time) is a demand risk since it is associated with the SC downstream operation.
- According to Ho et al. (2015) the first four risks identified in VW AE's SC (SC disruption risk; supply failure; supplier delay; lack of supplier capacity) can be classified as micro-risks, specifically supply risks since they constitute adverse events occurring upstream of the company. Once again, the first risk (SC disruption risk), despite being a major risk, would have to be classified as a supply-side risk, since the category that this author classified as *macro-risks* only include rare/extreme events subcategorized into natural risks and man-made risks. As the semiconductor disruption faced by the automotive industry is not a natural disaster nor a man-made disaster, it cannot be included in the *macro-risks* category. The fifth risk would be broadly classified as a micro risk, more specifically as an infrastructure risk and even more precisely as a transportation risk. The sixth risk would be broadly classified as micro risk, and more specifically as a manufacturing risk since it is associated with production. The last risk would be classified as a demand risk since happens downstream of the company.

To the best of my knowledge, these two types of classifications, despite being wide-ranging, have one common limitation: they do not include the possibility of existing a disruption that is not caused by natural disasters or man-made disasters. Therefore, a systemic disruption like the one that is affecting the semiconductor and automotive industries (Ramani et al., 2022), that was not originated from a natural disaster or a man-made disaster, would not be classified as disruption if does not exist a disruption risk responsible for originating it. In this way, it is crucial to create a new comprehensive classification of SCRs that encompasses in the disruption/catastrophic risk category (macro risk category) the subcategory "systemic risk". This new subcategory would include events responsible for originating systemic/market disruptions, that affect SCs and industries worldwide, such as the semiconductor crisis. This new comprehensive classification will also contribute to the need of studying systemic disruptions, identified by Ramani et al. (2022), since researchers tend to focus on disruptions that have an individual or local impact, instead of systemic disruptions that have a global impact.

In this way, this study suggests a new SCR classification, represented in Figure 15, which is an extension of the classification proposed by Ho et al. (2015). Therefore, this new classification encompasses two main types of risk, as Ho et al. (2015) proposed: micro-risks and macro-risks. Micro-risks are going to be considered frequent events that can happen inside the company's SC network, including the relationships established with partners located at all levels of the SC, or outside the company's SC network. This new classification is going to include all the micro-risks suggested by Ho et al. (2015) (demand, supply, manufacturing and infrastructure) as micro-risks "internal to the company´s SC network". Like Ho et al., (2015) did, infrastructure risk is going to be decomposed into information-technology risk, transportation risk and financial risk. Moreover, it is also going to be considered another new subcategory of micro-risks, named "external to the company's SC network" that includes political, environmental and social risks. Political risks are going to be considered threats related to political changes or policies that can change the company´s regulations and jeopardize the company´s operations. The development of European policies like Euro 6 or the new post-Euro 6, to limit air pollutant emissions from road transport (European Parliament, 2022), is a paradigmatic example of policies external to the company's SC network that affect OEM´s businesses. Social risks are related to social concerns that can put pressure on changing the company's activities. Protests or demonstrations to put pressure on OEMs to build electric cars instead of fossil-fuelled cars are an excellent example of social risks that can affect an organization. Environmental risks are threats related to climate change and environmental concerns that can endanger a company´s normal activity. In terms of macro-risks, three categories are going to be included: 1) natural risks; 2) man-made risks (these two as stated by Ho et al. (2015)); and 3) systemic risks. Natural risks include natural disasters (earthquakes, hurricanes, volcanic eruptions, floods, storms) and man-made risks comprise events associated with extreme human impact (terrorism, wars, pandemics, political or social revolutions). Systemic risks, as explained before, include events responsible for originating systemic/market disruptions, that affect SCs and industries worldwide, like the semiconductor crisis.

Another point that, to the best of my belief, was not addressed in the literature, is the dynamic evolution of micro-risks to macro-risks, this is, how the evolution in the severity of one micro-risk, or the conjunction of several micro-risks, can cause one macro-risk. In the case of the semiconductor crisis, it was the conjunction of several micro-risks that culminated in the disruption, namely the imbalance between the supply and the demand during the COVID-19 pandemic (section 4.2.4), this is, the conjunction of supply and demand risks was the main contributor to the systemic risk that originated the disruption. Another example of this evolution of micro-risks to macro-risks is the progression of political/social risks to political/social revolutions. If a wide set of political/social risks are brought together, they can originate a political/social disruption. However, this evolution of micro-risks to macro-risks must be adequately studied, remaining a research gap.

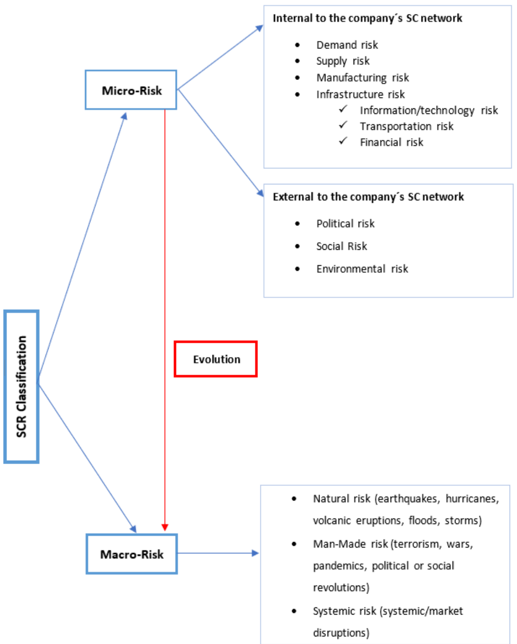

Figure 15 – Proposed SCR Classification

Table 6 sums up the comparison between the two SCR classifications analysed in the literature and the one developed.

Table 6 - SCRs classifications comparison

SCRs identified in VW AE's SC	**SCR Type/Classification according to** Wagner & Bode (2008)	**SCR Type/Classification according to** Ho et al. (2015)	**Proposed SCR Type/Classification**
1	Supply	Micro > Supply	Macro > Systemic
2, 3 and 4	Supply	Micro > Supply	Micro > Internal to the company´s SC network > Supply
5	Supply	Micro > Infrastructure > Transportation System	Micro > Internal to the company´s SC network > Infrastructure > Transportation System
6	-	Micro > Manufacturing	Micro > Internal to the company´s SC network > Manufacturing
7	Demand	Micro > Demand	Micro > Internal to the company´s SC network > Demand

5.2 Supply Chain Risk Assessment (SCRA)

After performing the SCRI stage, the SCRA stage is going to be developed. This is the second stage of every SCRM process and its main goal is to analyse and evaluate each risk in detail, namely, its likelihood of occurrence and the impact it can generate (Kern et al., 2012). In this way, the SCRs identified in VW AE's SC are going to be analysed in detail. Firstly, these risks are going to be defined and the causes and effects that they produced will be pointed out. Then, a SCR prioritization will be performed in order to select the risks that have a major impact on VW AE´s operations, since only these will be deeply analysed. The risk prioritization will be fed by the interview conducted with the SC manager, where she was requested to classify the impact of the identified SCRs on a qualitative scale of 1 to 5, being 1 the least impact and 5 the highest impact that a risk can produce in VW AE. After that, the selected risks are going to be analysed more in depth, namely the probability of occurrence will be estimated through the application of a BN, and a probability-impact risk matrix will be constructed to obtain the overall score of the production failure risk.

5.2.1 SCR causes, effects and prioritization

In the SCRA stage, the risks identified should be analysed, namely the associated causes and effects should be taken into consideration (Kern et al., 2012). Besides, a SCR prioritization must be performed since, as managing risks is a process that requires a substantial investment, companies cannot deal with all risks with the same urgency (Fan & Stevenson, 2018). As stated in section 4.3.2, this step helps companies to manage their limited risk resources and budget (Zsidisin, 2003). The SCR prioritization allows companies to define a sequence to treat risks, giving importance to the major ones, which usually are those that cause a great impact on a firm´s performance and/or have a great likelihood of occurrence. In this study, the SCR prioritization was performed by requesting to the SC manager during the interview to classify the impact that each risk identified produces in VW AE´s SC, through a qualitative scale of 1 to 5, being 1 the least impact and 5 the highest impact that the SCR can produce in VW AE´s operations.

Therefore, the causes and effects of the risks identified in VW AE's SC are analysed hereafter and the qualitative classification of SCRs impact asked to the SC manager is also pointed out:

1. <u>SC disruption</u> – This is considered the major risk that can affect a company and occurs when there is a systemic disruption that affects all operations of the company and all entities of the SC, including suppliers, the main company and customers. This major risk has been affecting VW AE due to the semiconductor crisis since this crisis originated not only the shortage of supplies but also the production failure of VW AE's plant and consequently the incapacity of delivering cars to customers, jeopardizing the whole upstream and

downstream SC. This risk occurred mainly during 2021 in VW AE and has a massive impact on VW AE´s operations. For that reason, the SC manager classified it with an impact of 5 on the qualitative scale of 1 to 5.

2. Supply failure – This risk occurs when a supplier fails its delivery and it can also be considered the main cause of the production failure risk. If supply failures occur on a regular basis, this can contribute to the SC disruption risk, this is, a sum of isolated supply failures can cause a systemic disruption. Despite not being so severe as the SC disruption risk, as VW AE has very low inventory levels due to the JIT/JIS policies, even an isolated supply failure can lead to production failure. For that reason, the SC manager classified it with an impact of 5 on the qualitative scale of 1 to 5.
3. Supplier Delay – This risk arises when happens a delay in delivering the supplies and can also culminate with the supply failure risk if it lasts for a long period. Therefore, it can be considered a cause of a supply failure. As VW AE works with JIT/JIS policies, even a small delay of JIT/JIS suppliers can have high repercussions on VW AE operation since obliges VW AE to modify its production schedule. Therefore, the SC manager classified it with an impact of 4 on the qualitative scale of 1 to 5.
4. Lack of supplier capacity – This risk happens when the supplier has no capacity to produce the subsystems/parts requested by the OEM. This lack of capacity can have several causes, such as: lack of sub-supplies; absence of workforce or machine breakdowns. This risk happened in 2022 since a sub-supplier of VW AE, located in Ukraine, suffered from lack a of production capacity due to the consequences of the war with Russia. However, the problem was solved and did not produce severe damages. Consequently, the SC manager classified it with an impact of 2 on the qualitative scale of 1 to 5.
5. Delay in transporting supplies – This risk happens when the carrier/3PL has difficulties in complying with the time window defined to deliver the material to VW AE's plant. This is a risk that usually occurs with distant suppliers (shelving suppliers) since JIT/JIS suppliers are located in the industrial park nearby VW AE's plant and, therefore, can easily deliver the suppliers if they have the material ready to ship. As semiconductors are, in the majority of the cases, included in subsystems delivered by JIT/JIS suppliers, this was not a major problem during the chip crisis. When this risk happened with distant suppliers, the especial transports, internally named SOFAs, were done to accelerate the delivery. Therefore, the SC manager classified it with an impact of 2 on the qualitative scale of 1 to 5.
6. Production Failure – This risk happens when there is a failure in the production of VW AE and encompasses two situations: the stoppage of the assembly line; and the production of incomplete cars. During 2021 and 2022 this risk occurred several times, either due to the

stoppage of the assembly lines or the production of incomplete cars, originated by the lack of semiconductor supplies. This production failure risk is mainly originated by supply failures and can contribute to originate a systemic disruption that affects the whole SC. For that reason, the SC manager classified it with an impact of 5 on the qualitative scale of 1 to 5.

7. Incapacity of satisfying car demand within normal lead time – This risk occurs when the OEM is not capable of delivering the number of cars needed to satisfy the demand within the normal lead time. This was a constant that affected VW AE´s SC during 2020-2022 and the semiconductor crisis, together with the COVID-19 pandemic, China's lockdown and the war in Ukraine, were the major factors that jeopardize the normal lead time. Indeed, instead of the usual lead time of 10 days, during this period the client had to wait 6-8 months. For that reason, the SC manager classified it with an impact of 5 on the qualitative scale of 1 to 5 since this incapacity of satisfying the demand in the normal lead time can affect the reputation and image of the entire VW group. This risk can also contribute to the systemic disruption that is currently affecting the automotive and semiconductor industries.

Therefore, considering the objectives of this work, the study´s boundary illustrated in Figure 7 and the VW AE's SC manager's opinion, it was decided to continue studying in the SCRM process two risks: supply failure and production failure. These two risks were selected since they were classified with an impact of 5 by the SC manager and are related to each other because supply failures are the main cause of production failure. Despite also having a classification of 5 on the impact scale of 1 to 5, the "incapacity of satisfying car demand within normal lead time" is not going to be studied since the focus of the this study is placed on the first-tier suppliers and the plant, as is stated in Figure 7. As a result, the downstream part of the SC falls out of this study´s boundary. Moreover, the SC disruption risk, although it is the major risk, as it is a systemic risk that results from the conjunction of others, it is very difficult to estimate its probability of occurrence, since it also requires information regarding the downstream part of the SC, which is out of the scope, as previously mentioned.

In this way, in the remainder of this work, the focus will be placed on the supply failure risk and production failure risk. The main objective of the next step is to estimate the probability of occurring a production failure in VW AE, taking into account the probability of a supplier failing its delivery.

5.2.2 Bayesian Network (BN) concepts

To obtain the probability of occurring a production failure in VW AE, which is the ultimate goal of this step, a network with the most relevant suppliers of semiconductors in VW AE's SC will be constructed. For doing this, the BN theory is going to be applied.

BNs are probabilistic graphical models, which constitute a rigorous method for the quantification of risks, uncertainty modelling and decision-making processes (Fenton & Neil, 2013). BNs represent networks of causes and effects through a set of variables (nodes) and a set of causal relationships (edges) that exist among the variables (Hosseini & Barker, 2016). These causal relationships between variables can be expressed with conditional probabilities. Different types of variables can be programmed in BN models, from quantitative to qualitative (high/medium/low) or Boolean (yes/no; true/false) (Hosseini & Ivanov, 2019). According to Hosseini & Ivanov (2020,b), BNs are a valuable method for SCR analysis, studying resilience and controlling the ripple effect of complex and interconnected systems for six major reasons: (1) BNs can capture the interdependencies among SC entities; (2) BNs can be developed with partial and uncertain information; (3) BNs can combine historical data and expert knowledge when there is a little historical data available (e.g., modelling the impact of disruptions); (4) BNs can incorporate the new information that arrives; (5) BNs can measure the impact of disruption of upstream entities on downstream entities; and (6) BNs allow the combination of data-driven integration with machine learning methods. Therefore, BNs are a suitable method for modelling the semiconductor SC disruption that is affecting VW AE's SC. Through the building of a BN, it is possible to represent the upstream part of VW AE's SC, namely the first-tier suppliers, and capture the interdependencies that exist between them. Taking into consideration the probability of existing a supply failure, it is possible to estimate the probability of occurring a production failure in VW AE.

In mathematical language, BNs are based on Bayes' theorem and conditional probability theory (Hosseini & Ivanov, 2019). The Bayes' theorem, represented in equation (1) allows us to think logically and rationally by obtaining the posterior probability of input data given new data input in a specific state (Hosseini & Ivanov, 2020b).

$$\mathrm{P}\ (\mathrm{A}|\mathrm{B}) = \frac{\mathrm{P}\ (\mathrm{B}|\mathrm{A}) \times \mathrm{P}(\mathrm{A})}{\mathrm{P}(\mathrm{B})} \qquad (1)$$

In this case, A represents the data input and B the new data imput, being $P\ (A|B)$ the posterior probability of A, considering the observed data B. $P\ (B|A)$ represents the likelihood function of the probability of new data B given A, being $P\ (A)$ the unconditional or prior probability distribution of the variable of interest A. $P\ (B)$ represents the marginal likelihood (evidence) (Hosseini & Ivanov, 2020b).

To mathematically represent the structure of a BN, let´s consider a BN with a set of nodes represented by $V = \{X_1, X_2, \dots, X_n\}$ and set of arcs E, which represent the causal relationships between variables. An outgoing arc X_{ij} represent a causal relationship between the nodes X_i and X_j, such that X_i is the parent of X_j and X_j is the child of X_i. In the context of SCRM, if we set X_i as a supplier of X_j, then the state of X_j depends on the state of X_i (Hosseini & Ivanov, 2019). There are three types of nodes in BNs: 1) root nodes, which are nodes without a parent node; 2) intermediate nodes, which are nodes with at least one parent and one child nodes and 3) leaf nodes, which are nodes without any child (Hosseini & Ivanov, 2019). The dependency between a child node and its parent node(s) is expressed through a conditional probability table (CPT). For root nodes, prior probabilities must be specified (Hosseini & Ivanov, 2019). Let´s consider a BN with five nodes, as illustrated in Figure 16.

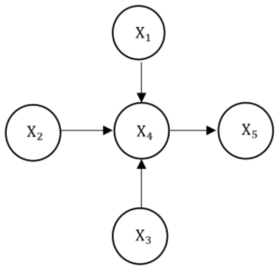

Figure 16 – Illustrative example of a BN

In the example illustrated in Figure 16, X_1, X_2, and X_3 are root nodes, while X_4 is an intermediate node and X_5 a leaf node. The prior probabilities $P(X_1)$, $P(X_2)$, and $P(X_3)$ and the conditional probabilities $P(X_4)$ and $P(X_5)$ have to be determined. The joint probability distribution of this BN can be expressed by equation (2).

$$\mathrm{P}(\mathrm{X}_1,\mathrm{X}_2,\mathrm{X}_3,\mathrm{X}_4,\mathrm{X}_5) = \mathrm{P}(\mathrm{X}_1)\times \mathrm{P}(\mathrm{X}_2)\times \mathrm{P}(\mathrm{X}_3)\times \mathrm{P}(\mathrm{X}_4|\mathrm{X}_1,\mathrm{X}_2,\mathrm{X}_3)\times \mathrm{P}(\mathrm{X}_5|\mathrm{X}_4) \quad (2)$$

The probability of individual variables can also be computed using the joint probability distribution (Hosseini & Ivanov, 2020b). If we are interested in obtaining the probability of X_5, then we had to use the expression represented in Equation (3).

$$\mathrm{P}(\mathrm{X}_5) = \sum_{\mathrm{X}_1,\mathrm{X}_2,\mathrm{X}_3,\mathrm{X}_4} \mathrm{P}(\mathrm{X}_1)\times \mathrm{P}(\mathrm{X}_2)\times \mathrm{P}(\mathrm{X}_3)\times \mathrm{P}(\mathrm{X}_4|\mathrm{X}_1,\mathrm{X}_2,\mathrm{X}_3)\times \mathrm{P}(\mathrm{X}_5|\mathrm{X}_4) \quad (3)$$

BN Modelling

For introducing the modelling of a BN, an example based on the work of Hosseini & Ivanov (2019) is presented. The BN can be used to model material flows, where each node represents a supplier. The direction of the material flow is given by the direction of each arc. Besides, it is going to be assumed that the rate of return flow is insignificant and therefore there are no cycles in the network. The relationship a $\longrightarrow$ b means that the materials are flowing from entity *a* to entity *b*. This also implies that a disruption in entity *a* can induce a disruption in entity *b*. Nevertheless, as it is assumed that there is no backwards flow, a disruption in a downstream entity does not imply a disruption in the upstream entities. Generally, it is going to be considered a network with n suppliers, $i = 1, \dots, n$, being each supplier represented in a node by X_i. The OEM, which is the target node, will be represented by OEM. Each supplier X_i can have 2 possible binary states: operational or disrupted. Each node X_i, whose parents, represented by M, are in state m, is in state x with a probability $P(x|m)$ and $\sum_x P(x|m) = 1$ for every realization of the states of parent nodes. The conditional probabilities $P(x|m)$ are named risk parameters and usually are represented in CPTs. As each node has two binary states, there are 2^n risk parameters at a node with n parents.

Consider a simple BN proposed by Hosseini & Ivanov (2019), formed by an OEM and two suppliers (X_1, X_2), as represented in Figure 17. The node OEM is conditioned on supplier nodes X_1 and X_2, which implies that the disruption of at least one supplier can induce the disruption of the OEM. The unconditional probabilities of each supplier are assumed to be 3%, which means that each supplier has a 3% probability of failing the supply to the OEM. The disruption of a supplier can cause a disruption of the OEM with a specific probability. The conditional probabilities of a disruption in the OEM due to the disruption in suppliers 1 and 2 are represented in Table 7.

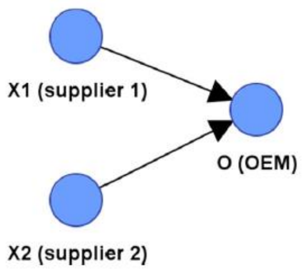

Figure 17 - BN example – Source: Extracted from Hosseini & Ivanov (2019)

Table 7 - CPT of OEM disruption. Extracted from Hosseini & Ivanov (2019)

Supplier 1 (X_1)	Operational		Disrupted	
Supplier 2 (X_2)	Operational	Disrupted	Operational	Disrupted
OEM disrupted	0.01	0.08	0.12	0.21
OEM operational	0.99	0.92	0.88	0.79

According to Table 7, the probability of the OEM being disrupted considering that supplier 1 is operational and supplier 2 is disrupted is 0.08. Besides, the probability of the OEM being disrupted if supplier 1 is disrupted and supplier 2 is operational is 0.12. If both suppliers are disrupted, the probability of existing a disruption in the OEM is 0.21. Considering the CPT and the Bayes' theorem, it is possible to compute the marginal probability of existing a disruption in the OEM, represented by equation (4):

$$P\ (\text{OEM disrupted}) = \sum_{X_1,X_2} \text{P(Supplier disrupted} \,|X_1, X_2) \times \text{P}(X_1) \times \text{P}(X_2) = \quad (4)$$

$$= \text{P(OEM disrupted}|X_1 = \text{disrupted}, X_2 = \text{disrupted}) \times$$

$$\times \text{P}(X_1 = \text{disrupted}) \times \text{P}(X_2 = \text{disrupted}) +$$

$$+ \mathrm{P(OEM\ disrupted|X_1 = disrupted, X_2 = operational)} \times$$
$$\times \mathrm{P(X_1 = disrupted)} \times \mathrm{P(X_2 = operational)} +$$
$$+ \mathrm{P(OEM\ disrupted|X_1 = operational, X_2 = disrupted)} \times$$
$$\times \mathrm{P(X_1 = operational)} \times \mathrm{P(X_2 = disrupted)} +$$
$$+ \mathrm{P(OEM\ disrupted|X_1 = operational, X_2 = operational)} \times$$
$$\times \mathrm{P(X_1 = operational)} \times \mathrm{P(X_2 = operational)} =$$
$$= (0.21 \times 0.03 \times 0.03) + (0.12 \times 0.03 \times 0.97) +$$
$$+(0.08 \times 0.97 \times 0.03) + (0.01 \times 0.97 \times 0.97) = 1.54\%$$

Thus, in this example developed by Hosseini & Ivanov, (2019), the probability of the OEM suffering from a disruption is equal to 1.54%. It is important to notice that eight risk parameters were required ($2^3 = 8$) to fill in CPT table because the network is composed of three nodes and each node has two binary states, as explained before.

5.2.3 VW AE´s BN model

Based on the previous example, a BN that represents VW AE's plant and the first-tier suppliers of semiconductor VW AE's SC was developed since the focus of this study is placed in these two echelons of the SC, as stated in Figure 7 (section 3.2.5). Considering the risk prioritization, only the two selected risks are going to be addressed in the BN (supply failure and production failure). The main goal is to estimate the probability of existing a production failure in VW AE's plant. This probability is determined through the probability of each supplier failing its delivery.

As explained in section 2.3.1, semiconductors are not used directly by the OEM because they are embedded into modules. These modules are, in turn, integrated into several subsystems of the car that are delivered by the first-tier suppliers (Matsuo, 2015). Therefore, in the first-tier of the BN, the first-tier suppliers that deliver the subsystems containing the semiconductor modules (X_1, X_2, X_3 and X_4) are going to be included. X_1 is a distant supplier responsible for delivering the radar sensor, which, as explained in section 2.3.1, is an integral part of the advanced driver assistance system, deployed for blind-spot detection, lane change assistance, collision mitigation or parking aid. X_2 is a distant supplier, responsible for supplying the doors subsystem that include door modules (low door module and high door module). X_3 is a JIS supplier, located in the industrial park nearby VW AE, and supplies the cockpit, which has a MIB, a display and a climatronic. X_4 is a JIT supplier located in the industrial park nearby VW AE and it is responsible for delivering the power steering subsystem, that contains power steering modules.

As in the previous example, each first-tier supplier, X_i, is represented by a node and can have two possible binary states: failure or not failure. The state failure occurs when the supplier fails the deliver to its VW AE's plant and not failure the opposite. The node production failure in VW AE is the ultimate node and it is conditioned on first-tier supplier nodes $X_1, \dots, X_4$, which implies that the failure of at least one supplier can induce the production failure of the VW AE. The node production failure in VW AE can have two possible binary states: failure or not failure. As explained in section 3.2.6, the shortage of microchips in suppliers and sub-suppliers can induce two distinct situations in VW AE. When the shortage is of indispensable subsystems, called job stoppers, without which the assembly cannot proceed, the assembly line is forced to stop until these subsystems are supplied. On the other hand, if the shortage occurs for components or parts that could be assembled a posteriori, the assembly continues and the car leaves the assembly stage incomplete. Therefore, two intermediate auxiliary nodes, job stopper and non-job stopper, were included in the BN to differentiate the supplies that can automatically stop the assembly line from the supplies that originate the production of incomplete cars. These two auxiliary nodes, represented by Y_i, can also have two states: failure and no failure. As in the example presented by Hosseini & Ivanov (2019), each node Y_i, whose parents, represented by X_i, are in state x, is in state y with a probability $P(y|x)$ and $\sum_y P(y|x) = 1$ for every realization of the states of parent nodes. The conditional probabilities $P(y|x)$ are risk parameters and usually are represented in a CPT. As each node has two binary states, there are 2^n risk parameters at a node with n parents. Only one supply, power steering, is a job stopper, being the others non-job stoppers. When the first-tier supplier X_4 fails to deliver the power steering subsystem, the production failure is certain.

The BN built is represented in Figure 18.

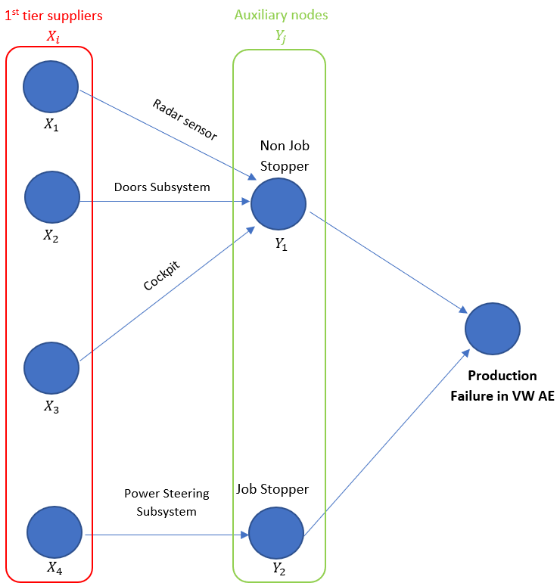

Figure 18 - Proposed BN for representing VW AE's Production Failure

The unconditional probabilities of each first-tier supplier, $X_1, \dots, X_4$, are assumed to be 3%, as stated by Hosseini & Ivanov (2019), which means that each supplier has a 3% probability of failing the delivery. The failure of a first-tier supplier can cause a failure in the VW AE's production with a specific probability (conditional probability). Each auxiliary node needs a CPT and, as a result, two CPT are needed. The CPT associated with the auxiliary node "non-job stopper" is going to have sixteen risk parameters ($2^4 = 16$) since each one of the four nodes (the "non-job stopper" and the three first-tier suppliers) has two binary states (failure and not failure). Applying the same reasoning, the CPT associated with the auxiliary node "job stopper" has only four risk parameters ($2^2 = 4$). The node "production failure in VW AE" results from the concatenation of the two auxiliary nodes. Therefore, the probability of occurring a production failure in VW AE will be the sum of the probability of a non-job stopper failure and a job stopper failure, this is, the probability of producing incomplete cars and the probability of existing a stoppage in the assembly line, respectively.

Missing Parts data collection, analysis and treatment

To compute the risk parameters needed to build the CPT associated with the non-job stopper node, was performed a missing parts data collection, analysis and treatment, which consisted of analysing the parts that were missing because of the semiconductor crisis. Due to these missing parts, first-tier suppliers failed several deliveries and, as a result, VW AE was unable to produce a large number of cars. The missing parts analysed were: radar sensors, door modules, MIBs, Climatronics, and Displays, this is, the semiconductor parts included in the subsystems that are non-job stoppers. As stated before, radar sensors are supplied by the first-tier distant supplier, door modules are included in the door subsystem supplied by another first-tier distant supplier, while MIBs, climatronics and displays are included in the cockpit, supplied by a JIS supplier. Each car has: 1 radar sensor, 2 door modules (1 low door module and 1 high door module), 1 MIB, 1 climatronic and 1 display. However, due to the different car specifications and personalization, had to be analysed: 1 type of radar sensor, 1 type of door module, 1 type of MIB, 11 types of climatronics and 3 types of displays.

The collected data included information regarding the missing parts per day from May 6th, 2021, to June 16th, 2022, this is, approximately one year and one month. This time period encompasses two distinct periods. On the one hand, includes part of 2021, where most of the missing parts occurred, since 2021 was the most severe year of the semiconductor disruption crisis in VW AE. On the other hand, includes part of 2022, when fewer missing parts occurred, because the semiconductor market slowly recovered since 2021. This data from different periods enriches the study, making it more comprehensive. Regarding data analysis, several steps were made. Firstly, the quantities per day of each type of missing part were summed in order to obtain the total value of each type of missing part. Then the quantities of the distinct types of climatronics and displays were summed, in order to obtain a total value of missing climatronics and displays.

In the case of the radar sensor, the total number of missing parts corresponds to the number of cars affected in VW AE, this is, the total number of incomplete cars produced. During the year and a month of data collection, 6371 parts were missing. As a result, 6371 cars were produced incomplete in VW AE due to X_1 missing parts.

In the case of the door's subsystem, each car has 1 low door module and 1 high door module. During the year of data collection, 2339 low door modules and 14315 were missing. To obtain the number of cars affected by the door missing parts, and avoiding duplicates, the following procedure was applied. In the days when only low door or high door modules were missing, the number of cars affected is equal to the number of low/high modules. In the days when low door and high door modules were missing, the number of cars affected was equal to the highest number of door modules missing on that day. This occurs because, when a shortage of both modules exists, the rule applied by the supplier is to optimize the losses and send a door subsystem without both door modules instead of sending two subsystems with missing parts. Thus, instead of sending one door subsystem without a low door module and another subsystem without a high door module, the supplier sends one subsystem with the two door modules missing since, applying this procedure, only one car is going to be affected instead of two. For instance, on the June 12th, 2021, 64 low door modules and 587 high door modules were missing. Therefore, the number of cars affected was equal to 587 (64 cars had low and high door modules missing and 523 had just high door module missing since $587 - 64 = 523$). The total number of cars affected with X_2 missing parts was equal to 14329.

In the case of cockpit, each cockpit has 1 MIB, 1 climatronic and 1 display. During the year of data collection, 6,234 MIBs, 14,278 climatronics and 972 displays were missing. To obtain the number of cars affected by these missing parts, and avoiding duplicates, the following procedure, similarly to the one applied in the door system, was conducted. In the days when only MIBs or climatronics or displays were missing, the number of cars affected is equal to the number of MIBs/climatronics/displays missing. In the days when two or three missing parts occurred, the number of cars affected was equal to the highest number in that day. Thus, the total number of cars affected with X_3 missing parts was equal to 18,209.

Table 8 sums up the cars affected (produced incomplete) due to missing parts of each first-tier non-job stopper supplier.

Table 8 - Incomplete Cars produced due to missing parts of each first-tier non-job stopper supplier

First-tier supplier	Incomplete cars produced
X_1	6,371
X_2	14,329
X_3	18,209

Model calculations

As it is very difficult to obtain the conditional probabilities needed, an estimation was performed. This estimation considers the percentage of incomplete cars produced due to missing parts of each first-tier non-job stopper supplier in the universe of the cars produced by VW AE, in the studied period. As VW AE produces approximately 200,000 cars per year (eleven months of production), from May 06th,2021, to June 16th, 2022, VW AE produced approximately 220,000 cars. In this way, the conditional probabilities (risk parameters) for the first CPT (the one build for the non-job stopper node) are the ratios between cars produced with missing parts due to the failure of each supplier and the total number of cars produced. Thus, the conditional probabilities (risk parameters) associated with the first CPT were computed as it is represented hereafter, from equation 5 to 12:

$$\mathrm{P(Non-job\ stopper\ failure|X_1 = failure, X_2 = failure, X_3 = failure)} = \frac{6{,}371+14{,}329+18{,}209}{220{,}000} \approx 0.177 \quad (5)$$

$$\mathrm{P(Non-job\ stopper\ failure|X_1 = failure, X_2 = failure, X_3 = no\ failure)} = \frac{6{,}371+14{,}329}{220{,}000} \approx 0.094 \quad (6)$$

$$\mathrm{P(Non-job\ stopper\ failure|X_1 = failure, X_2 = no\ failure, X_3 = failure)} = \frac{6{,}371+18{,}209}{220{,}000} \approx 0.112 \quad (7)$$

$$\mathrm{P(Non-job\ stopper\ failure|X_1 = failure, X_2 = no\ failure, X_3 = no\ failure)} = \frac{6{,}371}{220{,}000} \approx 0.029 \quad (8)$$

$$\mathrm{P(Non-job\ stopper\ failure|X_1 = no\ failure, X_2 = failure, X_3 = failure)} = \frac{14{,}329+18{,}209}{220{,}000} \approx 0.148 \quad (9)$$

$$\mathrm{P(Non-job\ stopper\ failure|X_1 = no\ failure, X_2 = failure, X_3 = no\ failure)} = \frac{14{,}329}{220{,}000} \approx 0.065 \quad (10)$$

$$\mathrm{P(Non-job\ stopper\ failure|X_1 = no\ failure, X_2 = no\ failure, X_3 = failure)} = \frac{18{,}209}{220{,}000} \approx 0.083 \quad (11)$$

$$\mathrm{P(Non-job\ stopper\ failure|X_1 = no\ failure, X_2 = no\ failure, X_3 = no\ failure)} = \frac{0}{220{,}000} = 0 \quad (12)$$

As $\sum_y P(y|x) = 1$, the conditional probabilities associated with the no failure of the non-job stopper node are complementary events of the conditional probabilities associated with the failure of the non-job stopper node and, as a result, the risk parameters associated with the no-failure of the non-job stopper node can be computed subtracting the risk parameters associated with the failure of the non-job stopper node to 1. Table 9 sums up all the risk parameters with the non-job stopper node.

Table 9 - CPT of the non-job stopper node

X_1	Failure				No Failure			
X_2	Failure		No Failure		Failure		No Failure	
X_3	Failure	No Failure	Failure	No Failure	Failure	No Failure	Failure	No Failure
Non-Job Stopper - Failure	0.177	0.094	0.112	0.029	0.148	0.065	0.083	0.000
Non-Job Stopper – No Failure	0.823	0.906	0.888	0.971	0.852	0.935	0.917	1.000

The marginal probability of occurring a failure in a non-job stopper can be computed using the conditional probabilities illustrated in Table 9 and the unconditional probabilities of each first-tier supplier, $X_1, \dots, X_4$, fail its delivery, that are assumed to be 3%, as stated by Hosseini & Ivanov (2019). Thus, as equation 13 represents:

$$\mathrm{P\ (Non\ Job\ Stopper\ failure)} = \sum_{X_1,X_2,X_3,} \mathrm{P(Non\ Job\ Stopper\ failure\ |}X_1, X_2, X_3) \times \mathrm{P}(X_1) \times \times \mathrm{P}(X_2) \times \mathrm{P}(X_3) = \tag{13}$$

$$= \mathrm{P(Non-job\ stopper\ failure|}X_1 = \mathrm{failure}, X_2 = \mathrm{failure}, X_3 = \mathrm{failure}) \times$$

$$\times \mathrm{P}(X_1 = \mathrm{failure}) \times \mathrm{P}(X_2 = \mathrm{failure}) \times \mathrm{P}(X_3 = \mathrm{failure}) +$$

$$+ \mathrm{P(Non-job\ stopper\ failure|}X_1 = \mathrm{failure}, X_2 = \mathrm{failure}, X_3 = \mathrm{no\ failure}) \times$$

$$\times \mathrm{P}(X_1 = \mathrm{failure}) \times \mathrm{P}(X_2 = \mathrm{failure}) \times \mathrm{P}(X_3 = \mathrm{no\ failure}) +$$

$$+ \mathrm{P(Non-job\ stopper\ failure|}X_1 = \mathrm{failure}, X_2 = \mathrm{no\ failure}, X_3 = \mathrm{failure}) \times$$

$$\times \mathrm{P}(X_1 = \mathrm{failure}) \times \mathrm{P}(X_2 = \mathrm{no\ failure}) \times \mathrm{P}(X_3 = \mathrm{failure}) +$$

$$+ \mathrm{P(Non-job\ stopper\ failure|}X_1 = \mathrm{failure}, X_2 = \mathrm{no\ failure}, X_3 = \mathrm{no\ failure}) \times$$

$$\times \mathrm{P}(X_1 = \mathrm{failure}) \times \mathrm{P}(X_2 = \mathrm{no\ failure}) \times \mathrm{P}(X_3 = \mathrm{no\ failure}) +$$

$$+ \mathrm{P(Non-job\ stopper\ failure|}X_1 = \mathrm{no\ failure}, X_2 = \mathrm{failure}, X_3 = \mathrm{failure}) \times$$

$$\times \mathrm{P}(X_1 = \mathrm{no\ failure}) \times \mathrm{P}(X_2 = \mathrm{failure}) \times \mathrm{P}(X_3 = \mathrm{failure}) +$$

$$+ \mathrm{P(Non-job\ stopper\ failure|}X_1 = \mathrm{no\ failure}, X_2 = \mathrm{failure}, X_3 = \mathrm{no\ failure}) \times$$

$$\times \mathrm{P}(X_1 = \mathrm{no\ failure}) \times \mathrm{P}(X_2 = \mathrm{failure}) \times \mathrm{P}(X_3 = \mathrm{no\ failure}) +$$

$$+ \mathrm{P(Non-job\ stopper\ failure|}X_1 = \mathrm{no\ failure}, X_2 = \mathrm{no\ failure}, X_3 = \mathrm{failure}) \times$$

$$\times \mathrm{P}(X_1 = \mathrm{no\ failure}) \times \mathrm{P}(X_2 = \mathrm{no\ failure}) \times \mathrm{P}(X_3 = \mathrm{failure}) +$$

$$+ \mathrm{P(Non-job\ stopper\ failure|}X_1 = \mathrm{no\ failure}, X_2 = \mathrm{no\ failure}, X_3 = \mathrm{no\ failure}) \times$$

$\times \text{P}(\text{X}_1 = \text{no failure}) \times \text{P}(\text{X}_2 = \text{no failure}) \times \text{P}(\text{X}_3 = \text{no failure}) =$

$= (0.177 \times 0.03 \times 0.03 \times 0.03) + (0.094 \times 0.03 \times 0.03 \times 0.97) + (0.112 \times 0.03 \times 0.97 \times 0.03) +$

$+ (0.029 \times 0.03 \times 0.97 \times 0.97) + (0.148 \times 0.97 \times 0.03 \times 0.03) + (0.065 \times 0.97 \times 0.03 \times 0.97) +$

$+ (0.083 \times 0.97 \times 0.97 \times 0.03) + (0.000 \times 0.97 \times 0.97 \times 0.97) =$

$= 0.00513 = 0.513\%$

In this way, the probability of a non-job stopper supplier failure is equal to 0.513 %, this is, the probability of producing incomplete cars is equal to 0.513 %.

As stated before, the CPT associated with the auxiliary node job stopper has only four risk parameters. If the supplier X_4 fails the delivery, the disruption occurs automatically, as stated in equation 14. Otherwise, the disruption does not happen, as shown in equation 15.

$$\text{P}(\text{Job stopper failure}|\text{X}_4 = \text{failure}) = 1 \quad (14)$$

$$\text{P}(\text{Job stopper failure}|\text{X}_4 = \text{no failure}) = 0 \quad (15)$$

As $\sum_y P(y|x) = 1$, thus:

$$\text{P}(\text{Job stopper no failure}|\text{X}_4 = \text{failure}) = 0 \quad (16)$$

$$\text{P}(\text{Job stopper no failure}|\text{X}_4 = \text{no failure}) = 1 \quad (17)$$

Table 10 sums up all the risk parameters with the job stopper node (failure and no failure).

Table 10 - CPT of the job stopper node

X_4	Failure	No Failure
Job Stopper - Failure	1.000	0.000
Job Stopper – No Failure	0.000	1.000

The marginal probability of occurring a failure in a job stopper can be computed using the conditional probabilities illustrated in Table 10 and the unconditional probabilities of the first-tier job stopper supplier, X_4, fails its delivery, that are assumed to be 3%, as stated by Hosseini & Ivanov (2019). Thus, as equation 18 represents:

$$\text{P}(\text{Job Stopper failure}) = \sum_{\text{X}_4} \text{P}(\text{Job Stopper failure}|\text{X}_4) \times \text{P}(\text{X}_4) = \quad (18)$$

$= \text{P}(\text{Job stopper failure}|\text{X}_4 = \text{failure}) \times \text{P}(\text{X}_4 = \text{failure}) +$

$+ \text{P}(\text{Job stopper failure}|\text{X}_4 = \text{no failure}) \times \text{P}(\text{X}_4 = \text{no failure})$

$= 1 \times 0.03 = 3\%$

Thus, the probability of existing a job stopper supplier failure is equal to 3%, this is, the probability of existing a stoppage in the assembly line is equal to 3%.

As stated before, the ultimate node (production failure in VW AE) results from the concatenation of the two auxiliary nodes. Therefore, the probability of occurring a production failure in VW AE will be the sum of the probabilities of job stopper and non-job stopper fail its delivery, this is, the sum of the probabilities of existing a stoppage in the assembly line and producing incomplete cars, respectively, as shown in equation 19.

$$\begin{aligned} \text{P (production failure in VW AE)} &= \text{P (Non Job Stopper failure)} + \text{P (Job Stopper failure)} \\ &= 0.513\% + 3\% = 3.513\% \end{aligned} \tag{19}$$

In this way, the probability of VW AE suffering from a production failure due to a failure of a first-tier supplier belonging to the semiconductor SC is equal to 3.513%.

As it is possible to notice, the probability associated with the job stopper supplier failure is somewhat higher than the probability associated with a non-job stopper supplier failure, this is, the probability of existing a stoppage in the assembly line is higher than the probability of producing incomplete cars. In this way, efforts must be placed to try to reduce the risk associated with the stoppage of the assembly line since it is the situation (risk event) that contributes the most to the production failure risk of VW AE. Besides, the probability associated with the job stopper failure is dependent of the prior probability of X_4 failing its delivery and, consequently, the probability of production failure is dependent of the prior probability of X_4 failure. In this way, the unconditional probabilities assumed to be equal to 3%, as stated by Hosseini & Ivanov (2019), might be having a considerable impact on the final probability of existing a production failure in VW AE. In the critical analysis chapter (chapter 6), these issues are going to be deeply explored.

After computing the probability of occurrence of the production failure risk and considering the impact associated with the risk, it is possible to build a probability-impact risk matrix. A probability-impact risk matrix is considered the most used method in SCRA, both by researchers and company practitioners (Fan & Stevenson, 2018). The probability-impact risk matrix built to assess the production failure risk is going to have two variables (probability and impact), such that each variable has an ordinal scale with five score levels. In the probability variable, each score level has one likelihood interval associated, as it is possible to see in Table 11. These intervals were based on the work of Raydugin (2012). The probability variable is a continuous quantitative variable, that is going to be fed by the probability obtained through the BN model. The impact variable considers the number of cars not produced in normal conditions and the definition of the five score levels can be consulted in Table 12. This definition was made considering the opinion of the VW AE´s SC manager. The overall risk scores were defined through the probability-impact risk matrix presented in Figure 19, in which the risk events are ordered in an impact-averse way, this is, the higher the impact score the higher the overall risk score. This probability-impact risk matrix was based on the work of Dinis et al., (2019). Moreover, it was used a colour-coded scheme to visualize risk events according to their overall risk score, in a total of five risk groups. Each definition of risk group, as well as the overall risk score associated with each risk group, can be consulted in Table 13.

In the case of the production failure risk of VW AE, the probability of occurrence was estimated as 3.513%, which belongs to the interval [0.1%;10.0%] and, therefore, has a score equal to 2. According to the VW AE´s SC manager, with this probability of occurrence, approximately 7,700 cars are not produced with normal conditions. In this way, since 7,700 belongs to the interval]5,000; 10,000], this risk has an impact score of 3. Therefore, the overall score of the production failure risk is equal to 12, which can be classified as a medium risk. This overall score is highlighted with a blue circle in the probability-impact risk matrix represented in Figure 19. Considering that the overall score of the production failure risk is medium, measures should be applied to decrease the probability of occurrence and/or the impact generated by the risk.

Table 11 - Ordinal Scale for probability of occurrence of the production failure risk

Score	Definition
5	Probability of occurrence of the production failure risk higher than 90%
4	Probability of occurrence of the production failure risk higher than 50% and lower or equal to 90%
3	Probability of occurrence of the production failure risk higher than 10% or lower or equal to 50%
2	Probability of occurrence of the production failure risk equal or higher than 0.1% and lower or equal to 10%
1	Probability of occurrence of the production failure risk lower than 0.1%

Table 12 - Ordinal Scale for impact of the production failure risk

Score	Definition
5	Number of cars not produced in normal conditions higher than 28,000
4	Number of cars not produced in normal conditions higher than 10,000 and lower or equal to 28,000
3	Number of cars not produced in normal conditions higher than 5,000 and lower or equal to 10,000
2	Number of cars not produced in normal conditions equal or higher to 1,000 and lower or equal to 5,000
1	Number of cars not produced in normal conditions lower than 1,000

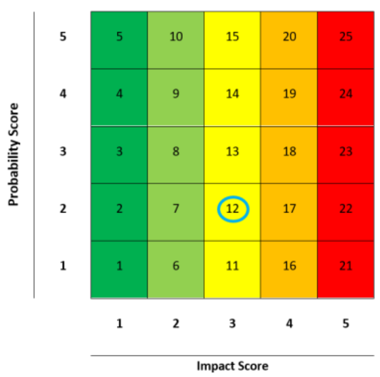

Figure 19 - Probability-Impact Risk Matrix

Table 13 - Risk Groups Definition

Risk Group Colour	Overall Risk Score	Definition
	21-25	Very High Risk
	16-20	High Risk
	11-15	Medium Risk
	6-10	Low Risk
	1-5	Very Low Risk

Through this comprehensive SCRA stage, it was possible to obtain an overall risk score for the VW AE's production failure risk, combining a quantitative method (a BN) with a qualitative approach (probability-impact risk matrix), which enriches the SCRM process. It is important to notice that this production failure risk is a result of other risks, namely: the stoppage of the assembly line; the production of incomplete cars and supply failures. Indeed, performing a root cause analysis, the supply failure risk is the major contributor to generating the production failure risk. Therefore, in the next stage of the SCRM process (SCRT), measures to address the supply failure risk and to strengthen the resilience of the semiconductor SC in the automotive industry are going to be adopted.

5.3 Supply Chain Risk Treatment (SCRT)

SCRT is the third stage of every SCRM process and can include five types of risk strategies, as stated in section 4.3.3: acceptance; avoidance; transfer; sharing; and mitigation (Fan & Stevenson, 2018). To treat the risks previously selected (supply failure and production failure), only risk mitigation is going to be thoroughly analysed. Risk acceptance is not applicable in this case since this strategy should be applied when a given risk has a low probability of occurrence and a low impact (Aqlan & Lam, 2015), and the production failure risk has a high impact on VW AE's operations. Risk avoidance should not be applied since this type of treatment is used when risks have a great probability of occurrence and a high estimated impact (Aqlan & Lam, 2015), which is not the case because the production failure risk has a low probability of occurrence. Risk transfer is a suitable strategy for some disruption risks, such as natural disasters or terrorist attacks (Aqlan & Lam, 2015). However, for systemic disruption risks, like the one that is affecting automotive companies due to the semiconductor crisis, and for operational risks, such as the production failure of VW AE, it is not an appropriate strategy. Risk sharing occurs when some risks are shared with other parties and it is suitable for dealing with risks with a low probability of occurrence and a high expected impact (Fan & Stevenson, 2018). As the production failure risk is mainly caused by the supply failures of first-tier suppliers, risk sharing is an option that should be explored by VW AE. In this way, it can be convenient to explore risk sharing clauses in the contracts established between VW AE and first-tier suppliers. These clauses should oblige suppliers to share the production failure risk when they fail their deliveries to VW AE. Nevertheless, despite being a strategy with potential, it produces limited results. Therefore, risk mitigation is the main risk treatment type selected to deal with the risks that arise from the semiconductor crisis.

Two semi-structured interviews were conducted to collect information regarding the risk mitigation strategies applied by VW AE to treat these risks associated with the semiconductor crisis. The semi-structured interview method was chosen because is widely used in literature to identify the main risk mitigation measures to deal with risks and raise SCRES in companies:

- Chen et al. (2019) used a series of semi-structured oral and written interviews, performed with managers in several functions, to collect information related to SCDs, namely the post-disruption SC recovery process.
- Spieske et al. (2022) analysed a healthcare SC in Europe, which has been severely affected by medical supplies shortages during the COVID-19 pandemic, in order to improve SCRES after a disruption. These authors interviewed thirty-nine experienced experts, who directly worked in COVID-19 services, to obtain information.
- Medina-Serrano et al. (2021) focused on studying SCRs of an automotive Germany company, to develop a SCRM process based on the guidelines of the ISO 31000. In the data collection phase, it was also used a semi-structured interview that cover several topics of SCRM, such as risk identification, evaluation or mitigation.
- Spieske et al. (2022) analysed the automotive SC network after the disruption originated by the COVID-19 pandemic to identify effective SCRES measures. The authors carried out thirty-five semi-structured interviews with experts carefully selected, namely OEMs and automotive suppliers, as their main data source.
- Scholten et al. (2014) investigated the interdependencies between the concept of SCRES and the operational disaster management process. A semi-structured interview protocol was used to obtain information regarding previous disasters, namely the effectiveness of the measures applied by the managers interviewed. Data regarding the proactive dimensions of preparedness and mitigation useful to build a SCRES framework was also provided by the nine interviewers.

In total, two oral interviews were performed during July 2022, in VW AE's installations, where the interviewees work. The selected interviewees were the SC manager and the logistics business unit manager since these high hierarchy levels are the ones responsible for taking decisions regarding the application of strategic risk measures to mitigate risks. The interviewees agreed to record the interview, which allows the collection of all information, and it is considered the most accurate interview documentation technique (Spieske, et al., 2022; Yin, 2014). It was developed an interview questionnaire to guide the interview and ensure the reliability and comparability of responses (Yin, 2014). This interview protocol, which can be consulted in section C.2 (appendix C), was based on a comprehensive literature review on disruption management and risk mitigation, and on previous questionnaires applied by researchers to study SCM topics in the automotive industry (Lechler et al., 2020; Medina-Serrano et al., 2021; Spieske, et al., 2022). The data collected was later analysed in a series of steps. Firstly, audio recordings were listened and carefully transcript. Afterwards, the transcribed interviews were shared with interviewees for final validation and some clarification, if needed (Yin, 2014). Then, data was organized and labelled into big topics, that encompass common or related information. Finally, the data was filtered in order to obtain only the most relevant information.

The first part of the interview questionnaire included information regarding the interviewee' personal data and experience, which can be consulted in Table 14. Then, questions regarding risk mitigation actions were asked, in order to know the measures already implemented by VW AE to deal with the semiconductor crisis and its impact. After that, several risk measures were proposed and discussed, so as to study their applicability in VW AE's operations. Finally, topics concerning SCRES were also discussed, to explore how VW AE´s SC can become more resilient and capable of dealing with future disruptions.

Table 14 - Interviewee' personal data and experience

Person	Role/Responsibility	Years in SCM	Years in automotive Industry
1	SC Manager	15	23
2	Logistic Business Unit Manager	3	27

5.3.1 Mitigation measures already implemented by VW AE

After acknowledging that there is a severe disruption in the SC of VW, caused by the semiconductor crisis, VW managers implemented several strategies to respond to the problem:

1. Firstly, at the factory level, they tried to understand when future supply failures would happen and if it would be possible to avoid them. Together with the suppliers and with the support of the purchasing centre in Germany, they mapped the entire SC of each VW plant, identifying the suppliers and sub-suppliers located at each tier, in order to understand their shortages in semiconductors, how these shortcomings would affect each plant and whether anything could be done to mitigate their effect. After that, VW managers tried to understand if it would be possible to find an alternative supplier to try to supply the specific semiconductor part that was missing.
2. Then, it was applied a process named "Banking". The main suppliers and sub-suppliers of VW complain about the lack of stability in orders since it was common to reduce or eliminate the orders when the factories stop for holidays in the summer and Christmas or when occurred a severe SCD. In these situations, due to that break in orders, the semiconductor sub-suppliers directed their semiconductors components produced to other companies that request more quantity or simply kept the level of orders stable, without any modification. Therefore, to avoid this problem, "Banking" has been applied, consisting of keeping the level of orders stable for semiconductor suppliers, this is, the quantity requested for that sub-suppliers

remained the same, regardless of the summer or Christmas holidays or even the occurrence of a SCD. Besides, this process also obliged VW AE or the first-tier suppliers to maintain a 15-day stock for semiconductor modules/subsystems. It is important to notice that normal automotive parts usually only have 3 days of stock, due to the JIT and JIS policies. Thus, VW factories and upstream suppliers had to create a commitment to keep the stock level of these semiconductor modules/parts during the period of holidays, until the new beginning of production, and to raise their normal level of modules' stocks to 15 days. This situation created new challenges for VW plants and first-tier suppliers, which had to arrange more warehouse space. Nevertheless, this order stability decreased the sub-supply failures and improved the availability of semiconductor components for the VW group, which also allow VW AE to decrease the production failure risk. Due to "Banking", modifications in the contracts with sub-suppliers had to be done, in order to create more stable long-term contracts, that assure that VW would buy every semiconductor component agreed, even on holidays or when SCDs occur.

3. Besides, a benchmarking was carried out with the competition, in order to understand which measures applied by competitors were having a positive impact on reducing the risks associated with the semiconductor crisis. From this process, two measures emerged:
    a. A focus on the most profitable car models was established, this is, in spite of producing every car model without any priority, it was decided to direct the few semiconductor modules available to the most profitable cars, in order to decrease the losses.
    b. The possibility of acquiring specific semiconductor components in the open market was introduced. In general, the VW engineering department is very judicious in adopting new suppliers, as it is very strict in the criteria that demand, which makes it not very open to alternative suppliers. However, with the impact that the semiconductor crisis was having on so many factories, this process became more flexible. As most of the time the lack was for a very small specific component (specific chip) and not for a final module, solutions were sought in the open market to fill the supply shortages of the contracted suppliers. In this way, the purchasing team sought in the open market which semiconductor was compatible with the desired features, to work as a substitute semiconductor for the one that was missing. Then, engineering teams carried out tests in order to validate its use. It was a joint task between purchasing and engineering teams. With the application of this process, was gained a lot of flexibility at the product level.

5.3.2 Proposed mitigation measures

In addition to the measures already implemented by VW AE, other measures were proposed by me and discussed during the interviews:

1. Firstly, the possibility of raising the level of stocks considering the criticality of the semiconductor supplier was discussed, this is, doing a selective "banking" process. In spite of obliging the VW AE plant or the first-tier suppliers to do a 15-day stock for every semiconductor modules/subsystems, it would be more convenient to perform an analysis to decide the level of stock that each plant or first-tier should have. In this way, analysing the historical data of suppliers´ reliability and the actual demand patterns would allow VW to differentiate the most critical suppliers from the others. Thus, the necessary level of stock would be determined according to the criticality of suppliers. Moreover, it would make more sense to raise stocks where the problem is located. During this semiconductor crisis, the supply failures were originated mainly due to the lack of semiconductors in second-tier or third-tier suppliers, which were not able to deliver modules to first-tier suppliers. Therefore, despite raising the stocks of final products/ subsystems in VW plants or first-tier suppliers' facilities, it would be more convenient to raise the stocks of raw materials (semiconductors or modules) in second or third-tier suppliers. As this is a problem of lack of semiconductors, and as in general first-tier suppliers have production capacity if they have the supplies that they need available, the stocks should be done upstream in the SC. This raise of stocks upstream also saves costs since it is much more difficult and costly to make and move stock of final subsystems than semiconductors or modules. Raising the level of stocks considering the criticality of the semiconductor supplier can be seen as a proactive mitigation measure since the increase of stocks is considered one of the most effective measures to foster redundancy (Sheffi & Rice, 2005).
2. Then, it was discussed the need to decrease complexity. VW is a group that not only offers a wide variety of car models to clients but also gives them a gigantic possibility of customization. In this way, in the same car model, there are hundreds of possible combinations that increase the complexity when managing the SC because more customizations imply more parts and suppliers to manage. The case of semiconductor modules is no exception. Contrary to other car brands, VW needs an enormous quantity of semiconductors to perform the required functions. An example presented by the logistics business unit manager was the case of the door modules, which vary from one car model to the other, despite having all similar functions, which obliges the sub-suppliers to produce several different modules, raising the human resources and the time needed to do it. This

different door modules increase the complexity and the difficulty of managing the suppliers. Besides, as each module is different and has a high degree of specification, it is very difficult to find a substitute. Finding a substitute more easily can decrease the supply failure and, therefore, decrease the probability of occurring future production failures. In this way, this reduction in complexity works also as an effective proactive mitigation measure since it decreases the probability of existing future failures and disruptions.

3. Connected to the decrease of complexity, it is essential the adoption of standardization and postponement. If, instead of several different door modules, VW requests only one or two standard types of door modules from suppliers, will highly decrease the complexity. Then, if needed, it can be done a software specification *a posteriori* in VW plants, this is, the product specification is delayed to a final step, which enhances product flexibility and decreases the dependency on a specific supplier. The adoption of standardization and postponement works also as a proactive measure (Hendricks & Singhal, 2011).
4. Another point suggested to VW AE's managers was the diversification of suppliers through multiple sourcing, which would allow VW AE to decrease the probability of occurrence of the supply failure risk and, as a result, also diminish the probability of the production failure risk. VW AE´s managers argued that it is very difficult to have multiple sourcing in first-tier suppliers since it would require a high investment in connecting all the electronic data interchange (EDI) systems of VW AE with the first-tier suppliers. This question of multiple sourcing is going to be further analysed in section 6.2. Nevertheless, they also pointed out that would make more sense to have a diversification of suppliers more upstream in the SC since it is there where the main supply issues are located and it is cheaper to invest in upstream suppliers than in downstream ones.

5.3.3 SCRES measures

These risk measures already implemented contribute to fostering SCRES in VW AE since they were applied after a disruption, as reactive measures, to diminish the negative impact of the semiconductor crisis in VW AE´s operations and facilitate the recovery and the continuity of the business (Ponomarov & Holcomb, 2009). Nevertheless, the concept of SCRES also encompasses the adaptative ability of a SC to be prepared for unexpected events (Ponomarov & Holcomb, 2009), this is, to achieve SCRES a company must adopt proactive measures, like the ones proposed. Moreover, other measures proposed and discussed during the interviews to foster SCRES were:

1. Establish a good collaborative relationship with suppliers. Historically, collaboration has been critical to VW AE since, as it works with JIS and JIT policies, suppliers, namely first-tier suppliers, play an important role in delivering the supplies in the correct sequence, in the

right quantities, at the right time and in the exact location. Nowadays, SCs are becoming more and more complex, interdependent and exposed to SCRs and SCDs (Shekarian & Mellat Parast, 2021). Therefore, more than ever, it is indispensable for VW AE to establish partnerships with suppliers, building with them solid relationships that allow sharing benefits but also risks (Ribeiro & Barbosa-Povoa, 2018). Besides, long term contracts should be built to apport confidence to suppliers.

2. Invest in SCRM methodologies. As stated in section 4.4.2, SCRES, as a descendant of SCRM, cannot be achieved separately, without involving the ideas and knowledge driven by SCRM (Pereira et al., 2014). In this way, if VW AE wants to build a resilient SC, SCRM methodologies, like the one developed during this master thesis, should be applied to study risks and threats comprehensively. Regardless of the techniques used in the various stages, it is critical to go through the entire SCRM process, identifying, assessing, treating and monitoring risks.

5.4 Supply Chain Risk Monitoring

As established in section 4.3.4, SCR monitoring is the last stage of every SCRM process and, perhaps, the least studied in the literature, remaining a research gap (Blackhurst et al., 2008). Although it has not been the focus of researchers, SCR monitoring is essential to continuously check the evolution of risk sources and the effectiveness of treatment strategies (Fan & Stevenson, 2018). Therefore, the SCR monitoring stage implies revisiting the three previous stages of the SCRM process, in order to identify possible new threats, assess the impact of existent risks and check the efficacy of treatment measures in mitigating the impact and reducing the probability of existent risks.

VW AE should invest in monitoring the risks associated with the semiconductor crisis, namely, the supply failure risk and the production failure risk. This monitoring process will allow VW AE to measure the efficacy that the already implemented measures are producing in containing the negative impacts of the identified SCRs. In this way, a continuous check will facilitate the adjustment or modification of the measures, if they are not producing the desired effects. Besides, this process of permanent observation also fosters the SCRI stage because it is easier to identify new threats or risk factors that can originate future disruptions. The monitoring stage should also be done to assess the performance of semiconductor suppliers/sub-suppliers in delivering the supplies needed, in order to be conscious of the probability of occurring a supply failure. Thus, the SCR monitoring stage should work as a feedback loop that revisits the previous stages of the SCRM process and a continuous improvement process, in order to incorporate the new imputs that are constantly arising from the surroundings. To do that, it is indispensable the collaboration of all SC workers, that must be aware of the importance of the SCR monitoring stage and the role that each one should play.

With the purpose of pointing out some good practices, it was developed a stakeholder engagement process that is important for VW AE in the process of monitoring the SCRs it faces. This stakeholder engagement process can be consulted on section C.3 (appendix C).

5.5 Chapter conclusions

The SCRM process developed during this chapter enabled the comprehensive study of VW AE´s semiconductor SC, addressing the semiconductor crisis that has been affecting the company, the VW group and the whole automotive industry. In this way, this process permitted not only identifying the SCRs that VW AE has been facing, but also assessing the probability of occurrence and the impact of the production failure risk. Moreover, the SCRT stage also made it possible the identification and analysis of the mitigation measures already implemented by VW AE, the proposal of new mitigation measures and the discussion of important measures for fostering SCRES. The main limitation of this methodology might have been the assumption of the prior probability of occurring a supply failure. Although this assumption was based on literature, it might have impacted the estimation of the probability of occurring a production failure and, as a result, the calculus of the overall risk score since the production failure risk is mainly caused by the supply failure risk. Therefore, to study the impact of this limitation on the estimation of the probability of occurring a production failure, it is going performed a sensitivity analysis in section 6.1.

6 Critical analysis

This chapter has the goal of critically analysing the methodology used in this study, this is, the SCRM process, namely some topics of the SCRA and SCRT stages. Thus, in section 6.1., concerning the SCRA stage, a sensitivity analysis to the assumed unconditional probability of occurring a supply failure in a first-tier supplier is going to be performed, in order to see the impact of this parameter on the final probability of occurring a production failure in VW AE and on the overall risk level. In section 6.2, regarding the SCRT stage, the possibility of dual-sourcing, adding a new first-tier supplier, is also going to be explored and the probability of production failure considering different prior probabilities of supply failure and different sourcing strategies is going to be analysed.

6.1 Sensitivity analysis

In the SCRA stage, during the design of the VW AE's BN model, it was assumed that the unconditional probabilities of each first-tier supplier, $X_1, \dots, X_4$ were equal to 3%, as stated by Hosseini & Ivanov (2019), which means that each supplier had a 3% probability of failing the delivery to VW AE. Nevertheless, considering the impact that the semiconductor crisis had on the operations of first-tier automotive suppliers, leading to several disruptions, this probability might be underestimated. Therefore, that was an assumption with a considerable level of uncertainty, that might have affected the calculation of the final probability of occurring a production failure in VW AE. In this way, it is indispensable to perform a sensitivity analysis of this parameter, in order to assess the impact that the value has on the final probability. This parameter was varied in minus two percentual points (pp), plus two pp, and plus five pp, this is, it was considered a probability of occurring a supply failure equal to 1%, 5% and 8%, respectively. Then, the same procedure done in the SCRA stage to obtain the probability of occurring a production failure in VW AE was performed. The results are summed up in Table 15. Thus, with the prior probability of each supplier failing its delivery equal to 1%, 5% and 8%, it was obtained a probability of occurring a production failure equal to 1.177%, 5.885% and 9.412%, respectively. In this way, it is possible to verify that the prior probability of occurring a supply failure is a sensible parameter, which has a high impact on the final probability of occurring a production failure.

Moreover, it is important to notice that, in the SCRA stage and here, it was assigned the same probability of existing a supply failure to all first-tier suppliers, which, in general, does not correspond to reality since the reliability of deliveries of each first-tier supplier can be different, depending on its capacity, resources and overall operational efficiency.

Table 15 - Sensitivity analysis to the prior probability of occurring a supply failure and impact in the final probability

Variations of the supply failure probability	-2pp (1%)	3%	+2pp (5%)	+5pp (8%)
Probability of occurring a production failure in VW AE	1.177%	3.513%	5.885%	9.412%

Indeed, considering that the semiconductor crisis highly affected the capacity of first-tier suppliers to deliver the supplies to OEMs, the scenario that considers the probability of occurring a supply failure equal to 8% might be more realistic than the one considered in the methodology and discussion chapter. If it is considered the probability of occurring a supply failure equal to 8%, the probability of occurring a production failure in VW AE will be equal to 9.412%, as stated in Table 15. In this case, according to the ordinary scale of the probability variable, the probability score of existing a production failure will remain at 2 because $9.412\% \in [0.1\%; 10.0\%]$. According to the VW AE´s SC manager, with this probability of occurrence, approximately 20,700 cars are not produced with normal conditions. In this way, since 20,700 belongs to the interval]10,000; 28,000], this risk has an impact score of 4. Therefore, the overall score of the production failure risk is equal to 17, which can be classified as a high risk. This overall score is highlighted with a blue circle in the new probability-impact risk matrix represented in Figure 20. In this way, an increase of 5 pp in the probability of occurring a supply failure implies an increase in the final overall risk score of VW AE's production failure that evolves from medium to high. This change in the overall risk score modifies the urgency of applying mitigation measures. If VW AE suffers from such a high level of risk, all efforts must be placed on decreasing the probability of occurring this risk, applying immediately a set of effective measures, in which the proposed measures of section 5.3 must be included.

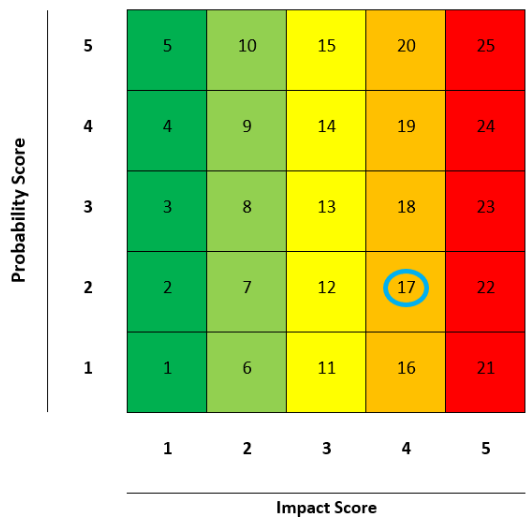

Figure 20 - New Probability-Impact Risk Matrix

6.2 Scenario analysis

In the SCRT stage (section 5.3), in the step of proposed mitigation measures, the diversification of first-tier suppliers through multiple sourcing was mentioned as a possible strategy to diminish the probability of occurrence of the supply failure risk and, as result, also to decrease the probability of occurrence of the production failure risk. However, this question was not explored in detail. If we go back to the SCRA stage, we can recover the following equation:

$$\mathrm{P\ (production\ failure\ in\ VW\ AE)} = \mathrm{P\ (Non\ Job\ Stopper\ failure)} + \mathrm{P\ (Job\ Stopper\ failure)} = \\ = 0.513\% + 3\% = 3.513\% \quad (20)$$

As it is possible to notice, the probability associated with the job stopper supplier failure is much higher than the probability associated with a non-job sopper supplier failure, this is, the probability of existing a stoppage in the assembly line is much higher than the probability of producing incomplete cars. In this way, efforts must be placed to try to reduce the risk associated with the stoppage of the assembly line since it is the situation (risk event) that contributes the most to the production failure risk of VW AE. One possible measure to reduce the supply failure risk and, as result, reduce the risk associated with the stoppage of the assembly line is multiple sourcing. In this case, another supplier that complements the work of the first-tier supplier X_4 is going to be added, this is, a dual-sourcing supplier policy for the job stopper node is going to be adopted. Therefore, the proposed BN represented in Figure 18 will suffer a modification to include the new first-tier supplier X_5. The new BN is represented in Figure 21.

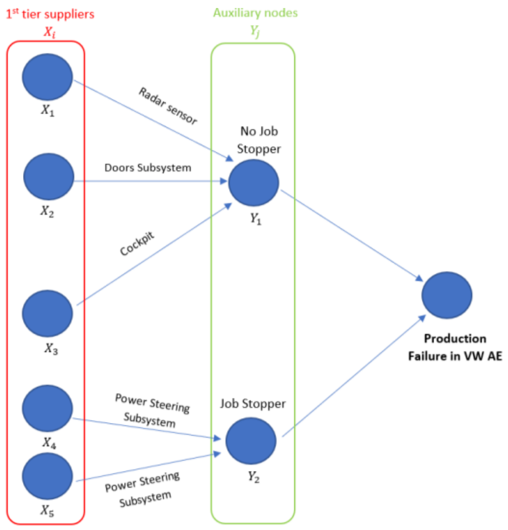

Figure 21 - New BN considering dual-sourcing in the job stopper node

With this new BN that considers dual-sourcing in the job stopper node, the final probability of the production failure in VW AE had to be recalculated. As the non-job stopper node did not suffer any modification, remaining the single source policies associated with X_1, X_2 and X_3, the probability associated with the non-job stopper failure remains the same, this is:

$$\text{P (Non Job Stopper failure)} = 0.513\% \quad (21)$$

However, the probability associated with the job stopper supplier failure will be different since it was added an extra first-tier supplier (X_5). As these two suppliers deliver the same subsystem, it is going to be considered that they have the same importance to VW AE, this is, the material flows needed by VW AE are equally divided by the two suppliers. Besides, it is considered that, if one supplier does not have the capacity to deliver the supplies needed, the other one can replace the failure of the first one. In this way, these two suppliers work as backup suppliers of each other and, as a result, a supply failure only occurs when both suppliers fail. Therefore:

$$\text{P(Job stopper failure}|\text{X}_4 = \text{failure}) = \text{P(Job stopper failure}|\text{X}_5 = \text{failure}) = 50\% = 0.5 \quad (22)$$

$$\text{P (Job Stopper failure)} = \text{P(Job stopper failure}|\text{X}_4 = \text{failure}, \text{X}_5 = \text{failure}) \times$$
$$\times \text{ P}(\text{X}_4 = \text{failure}) \times \text{ P}(\text{X}_5 = \text{failure}) \quad (23)$$

Here two scenarios are going to be considered: scenario A, and scenario B. In scenario A, the probability of each first-tier supplier X_4 and X_5 failure its delivery is assumed to be 3%, as proposed by Hosseini & Ivanov (2019), while in scenario B this probability is considered to be 8%. Therefore, performing the calculations for both scenarios, we can obtain the following probabilities of job stopper failure:

Scenario A: $\text{P (Job Stopper failure)} = 1 \times 0.03 \times 0.03 = 0.09\,\%$ (24)

Scenario B: $\text{P (Job Stopper failure)} = 1 \times 0.08 \times 0.08 = 0.64\%$ (25)

Analysing both values, it is possible to verify that, despite different, both are lower than the original scenario, where the probability of existing a job stopper failure was equal to 3%. After this, it is possible to compute the final values of the probability of production failure in VW AE for both scenarios:

Scenario A:

$$\text{P (production failure in VW AE)} = \text{P (Non Job Stopper failure)} + \text{P (Job Stopper failure)} =$$
$$= 0.513\% + 0.09\% = 0.603\,\% \quad (26)$$

Scenario B:

$$\text{P (production failure in VW AE)} = \text{P (Non Job Stopper failure)} + \text{P (Job Stopper failure)}$$
$$= 0.513\% + 0.64\% = 1.153\,\% \quad (27)$$

In the original scenario, with single sourcing and with a prior probability of existing a supplier failure equal to 3%, the probability of existing a production failure in VW AE was equal to 3.513%. Then, with single sourcing and with a prior probability of existing a supplier failure equal to 8%, it was obtained the probability of existing a production failure in VW AE equal to 9.412%. After that, with dual-sourcing and with a prior probability of existing a supplier failure equal to 3%, the probability of existing a production failure in VW AE was equal to 0.603%. Besides, with dual-sourcing and with a prior probability of existing a supplier failure equal to 8%, the probability of existing a production failure in VW AE was equal to 1.153%. This data is summed in Table 16.

Table 16 - Summary of production failure probabilities considering single and dual-sourcing

Prior probability of supply failure	3%	8%
P (production failure in VW AE) considering single sourcing	3.513%	9.412%
P (production failure in VW AE) considering dual-sourcing	0.603%	1.153%
Difference in P (production failure in VW AE) between single and dual-sourcing	-2.91pp	-8.259pp

With the prior probability of existing a supplier failure equal to 3%, if the probabilities of production failure in VW AE in single and dual-sourcing are compared, it is possible to conclude that the dual-sourcing policy would allow VW AE to decrease the probability of production failure in -2.91pp, as stated in Table 16. Moreover, with the prior probability of existing a supplier failure equal to 8%, if the same comparison is done, it is possible to conclude that the dual-sourcing policy would allow VW AE to decrease the probability of production failure in -8.259pp, as shown in Table 16. In addition, if the single and multiple-sourcing policies in the cases with the same prior probability of supply failure are compared, it is possible to conclude that, the higher the prior probability of supplier failure, the higher the benefits of applying dual-sourcing since the decrease in the probability of existing a production failure increases with the rise of the prior probability of supply failure. Overall, it is possible to conclude that, regardless of the prior probability of supply failure, the implementation of dual-sourcing is a beneficial strategy to decrease the probability of occurring a production failure in VW AE.

Nevertheless, it would be important to perform a cost-benefit analysis to measure if it is economically viable for VW AE implementing the dual-source policy. On the one hand, as it was shown, the dual-sourcing would allow VW AE to decrease the probability of the production failure risk. It would be important to quantify this reduction in the probability in terms of economic savings. On the other hand, this solution would have several costs associated. Adding a new first-tier supplier in an automotive SC is very costly because the Electronic Data Interchange (EDI) systems of the OEMs need to be connected with the EDI systems of the first-tier suppliers, in order to obtain an updated and reliable flow of information. Considering that OEMs work with JIT and JIS policies, the information flows are critical to making sure these policies work properly. Then, the economic savings would have to be compared with the costs of adding a new supplier to make a final decision of applying the dual-sourcing policy. This cost-benefit analysis will be left for future work.

7 Final conclusions and future work

The closing chapter of this master thesis focuses on presenting the final conclusions of the work and pointing out the relevant aspects and research avenues to be considered in the future. Therefore, in section 7.1 a summary of the work is made and the main contributions to VW AE and the literature are highlighted, and in section 7.2 the main research topics to be explored in the future are presented.

7.1 Final conclusions

The automotive sector has been facing a major SCD due to semiconductor shortages, induced by the COVID-19 pandemic (Ramani et al., 2022). This worldwide semiconductor crisis has been causing a massive ripple effect that has affected worldwide automotive companies. In the second chapter, a thorough study of the automotive and semiconductor industries was made, in order to understand the semiconductor disruption problem that the automotive industry is facing. The main characteristics of both industries were presented, the importance of semiconductors in the automotive industry was explained, and the risks and paradigmatic disruptions in the interface between both industries were also highlighted. Then, a comprehensive literature review was developed with the main objective of investigating the concepts associated with the semiconductor crisis problem, presenting the major research topics related to disruption management. Thus, the concepts of SCD, SCRM and SCRES, as well as the relationships existent between them, were scrutinized. This literature was also critical to examine which models were suitable to analyse the problem, having been chosen the SCRM process as the main methodology to address the problem since it permits studying in a holistic way the SCRs existent in VW AE´s semiconductor SC. Firstly, the SCRI stage, through the development of six semi-structured interviews with SC specialists, enabled the identification of several SCRs, which were classified according to two existing risk classifications and one new proposed classification. Then, the identified SCRs were analysed and a risk prioritization was performed to select the most relevant risks (supply failure and production failure). After that, a BN model was designed to capture the VW AE´s semiconductor upstream SC and compute the probability of occurring a production failure considering the probability of existing a supply failure. A probability-impact risk matrix was built to compute the overall risk score of the production failure risk. In the SCRT stage, two semi-structured interviews were done to identify and analyse the mitigation measures already implemented by VW AE and discuss new mitigation and SCRES measures. It was also briefly explained the importance of SCR monitoring stage to VW AE and it was developed a stakeholder engagement process with the purpose of pointing out some good practices. Finally, it was performed a critical analysis to study the impact of the main limitation of the study and the possibility of VW AE adding a new supplier, following a dual-sourcing policy in the job-stopper supplier.

To the best of my knowledge, this work is a novelty since it is the first one that applied the SCRM process to the semiconductor crisis that the automotive industry is facing, contributing also to the literature on SCD, SCRM and SCRES fields. Besides, this master thesis also bridged the gap presented by Ho et al. (2015), who stated most of the works in the literature that apply the SCRM process are theoretical in nature and have not been validated empirically. Therefore, through the application of the SCRM process to a real automotive company, VW AE, this work contributed to overcoming this gap, raising awareness of the importance of SCRM process in real companies. Moreover, Louis & Pagell (2019) stated that SCRI is the less studied stage of SCRM and existed a research gap that urged to be explored. This work also contributed to this research gap, through the development of a new comprehensive risk categorization. Besides, this study also contributed to the need of studying systemic disruptions, identified by Ramani et al. (2022), like the semiconductor disruption. Finally, this master thesis constitutes another example that, as stated by Hosseini & Ivanov (2020), the application of BNs to the field of SCRM and resilience is a powerful and promising area of interest for both researchers and practitioners, that needs to be explored.

7.2 Future work

It would be important to continue studying the semiconductor shortage problem in the automotive industry, in order to complement the work developed in this master´s thesis with further investigations. Firstly, one aspect to be considered in future research is the supplier perspective, which is under-represented in the literature (Fan & Stevenson, 2018). As disruptions in OEMs are mainly caused by upstream disruptions in suppliers, it would be crucial to develop SCRM processes that reflect not only the views of OEMs but also the insights of suppliers located in several upstream tiers. This would enable the study of SCDs from different angles, which would enrich the study. In the case of this master thesis, this will imply widening the study's boundary defined in Figure 7. It would be also important to study the dynamic evolution of micro-risks to macro-risks since, to the best of my knowledge, this is an under-researched topic in literature, remaining a research gap. Moreover, regarding the stages of the SCRM process, it is critical to invest in studying risk monitoring since it has received little attention in this work and it is also the least studied process in the literature (Fan & Stevenson, 2018; Ho et al., 2015). Finally, it would be indispensable to quantify the benefits and costs associated with SCRM stages and measures in order to attract more companies in applying SCRM processes. Indeed, a specific topic of this master´s thesis that urges to be studied in the future is the cost-benefit analysis of applying the dual-sourcing policy proposed to VW AE, as was stated in section 6.2. This cost-benefit analysis would provide VW AE´s decision-makers with all relevant data to make a more reliable decision.

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Appendix A – Automotive and semiconductors industries

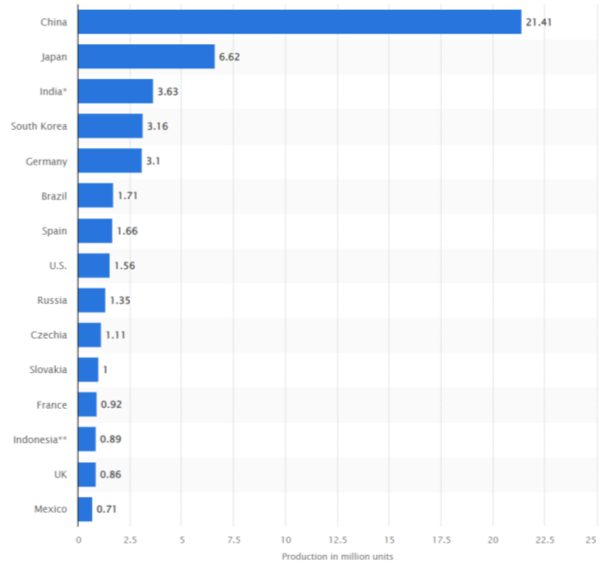

Figure A. 1 – Passenger cars produced in 2021 (million units). Source: Extracted from (Statista, 2022a)

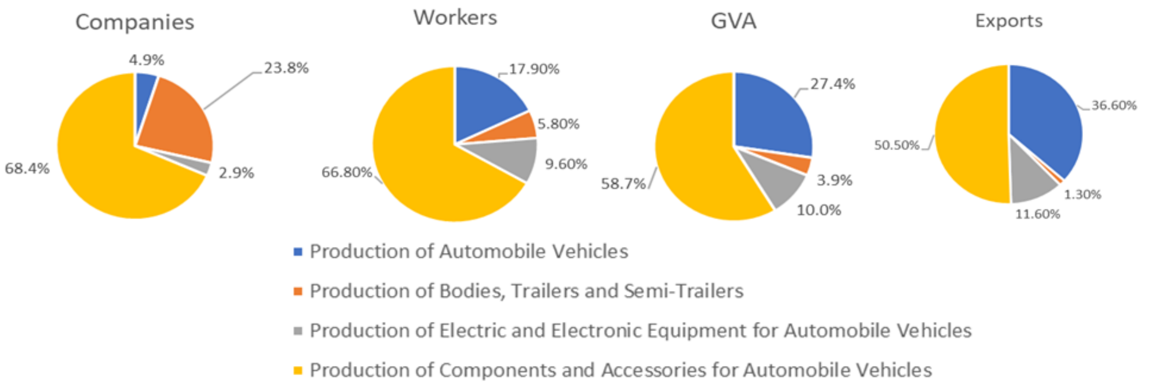

Figure A. 2 - Distribution of companies, workers, gross value added (GVA) and exports within the automotive subsectors. Source: Adapted from *(Jordão & Fernandes, 2022)*

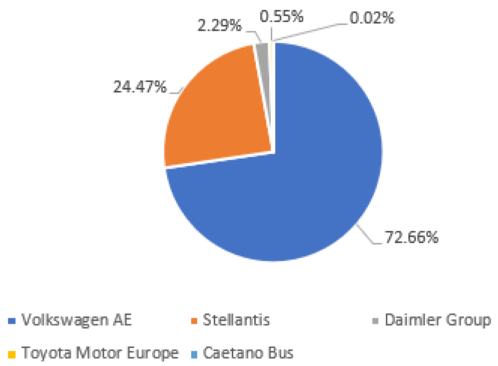

Figure A. 3 - Distribution of vehicles produced in Portugal according to the manufacturer. Source: (Fábio Carvalho da Silva, 2021)

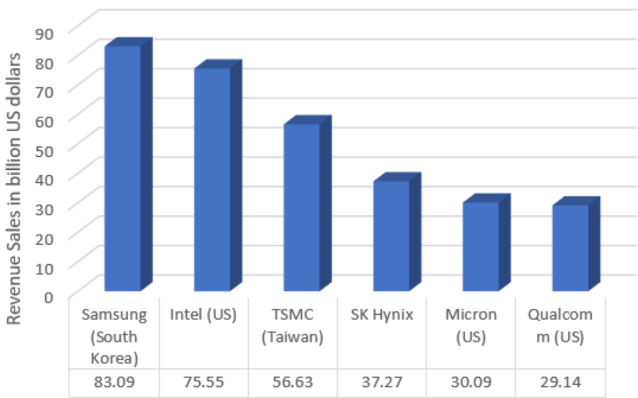

Figure A. 4 - Leading Semiconductor Companies in 2021 by sales revenue. Source: Adapted from (Statista, 2022e)

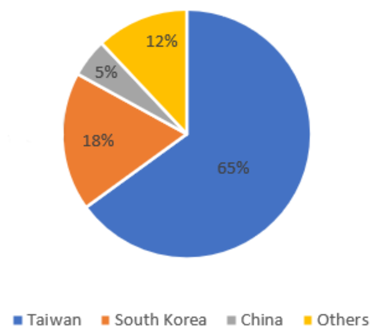

Figure A. 5 - Semiconductor foundries revenue share worldwide in 2021, by country. Source: Adapted from (Statista, 2022d)

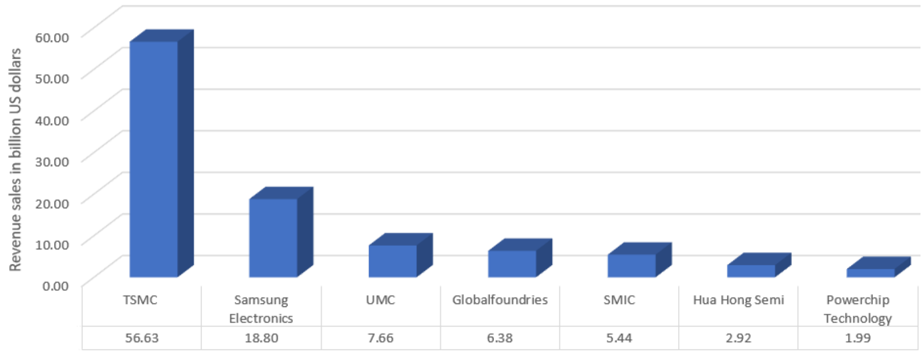

Figure A. 6 - Leading semiconductor foundries worldwide in 2021 by revenue sales. Source: Adapted from (Statista, 2022c)

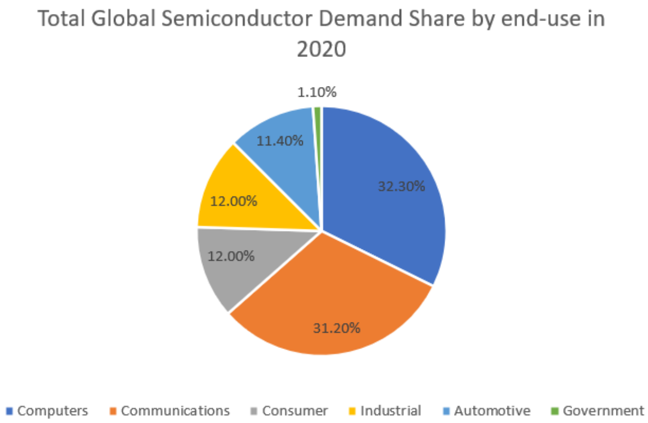

Figure A. 7 – Total Global Semiconductor Demand Share by end-user in 2020. Source: (Semiconductor Industry Association, 2021)

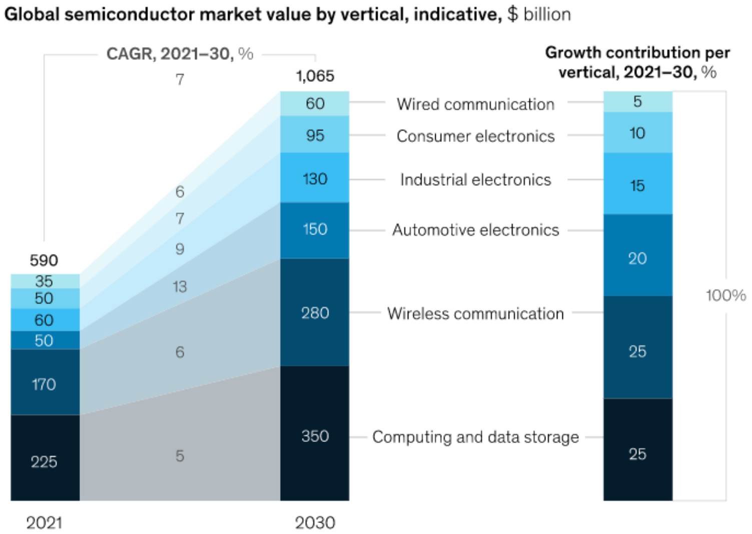

Figure A. 8 - Global semiconductor market value per segment in 2021 and 2030, in billion dollars. Source: Extracted from (Mckinsey, 2022)

Appendix B – Literature review

Table B. 1 - Sum-up of relevant disruptions. Source: Extension from Dolgui et al., 2018

Disruption Factor	Example	Impacts
Terrorism	September 11	Five Ford plants were closed for a long time
Piracy	Somali, 2008	Breaks in many SCs
Natural Disasters	Earthquake in Thailand, 1999	Apple computers' production in Asia was paralysed
	Flood in Saxony, 2002	Significant production decrease at VW, Dresden
	Hurricane Katrina, 2006	This storm halted 10% - 15% of total US gasoline production, raising both domestic and overseas oil prices
	Earthquake in Japan, 2007	Production breakdown in Toyota's SCs amounted to 55,000 cars
	Earthquake and tsunami in Japan, 2011	Massive collapses in global automotive and electronics SCs; Toyota lost its market leadership position
	Floods in Chennai, India in 2015	Production of academic literature was stopped at many international publishing houses
Man-made disasters	Explosion at BASF plant in Ludwigshafen in 2016	15% of raw materials were missing for the entire SC; Production of some products at BASF were stopped for many weeks
	Fire at distribution centre of e-commerce retail company ASOS in 2005	Delivery stopped for a month
	A fire in the Phillips Semiconductor plant in Albuquerque, New Mexico in 2000	Phillips's major customer, Ericsson, lost $400 million in potential revenue
Political Crisis	Gas crisis 2009	Breaks in gas supply from Russia to Europe, billions of losses to GAZPROM and customers
Financial crises	Autumn 2008	Production decrease or closing; breaks in SCs throughout
Strikes	Strikes at Hyundai plants in 2016	Production of 130,000 cars was affected
Legal contract disputes	Volkswagen and Prevent Group contract dispute in summer 2016	Six German factories face production halt on parts shortage; 27,700 workers are affected, with some sent home and others moved to short-time work
Trade-block	Obstruction of the Suez Canal in March 2021	The obstruction caused a massive chaos to the international trade-market
Pandemics	COVID-19 pandemic	Disruptions in many SC around the world, such as automobile SC, that suffered due to the semiconductor crisis. The ripple effect was greater than ever, contributing to propagate the negative impacts downwards on SC, affecting several echelons

Table B. 2 - SCRM definitions. Source: João Azinhais

Authors	Definitions of SCRM
(Jüttner et al., 2003)	The identification and management of risks for the supply chain, through a coordinated approach amongst supply chain members, to reduce supply chain vulnerability as a whole
(Norrman & Jansson, 2004)	To collaborate with partners in a supply chain, apply risk management process tools to deal with risks and uncertainties caused by, or impacting on, logistics related activities or resources
(Tang, 2006)	The management of supply chain risks through coordination or collaboration among the supply chain partners so as to ensure profitability and continuity
(J. H. Thun & Hoenig, 2011)	Characterised by a cross-company orientation aiming at the identification and reduction of risks not only at the company level, but rather focusing on the entire supply chain
(Ho et al., 2015)	An inter-organisational collaborative endeavour utilising quantitative and qualitative risk management methodologies to identify, evaluate, mitigate and monitor unexpected macro and micro level events or conditions, which might adversely impact any part of a supply chain
(Aqlan & Lam, 2015)	A systematic approach for identifying, assessing, mitigating, and monitoring potential disruptions in the supply chain in order to reduce negative impact of these disruptions on supply chain operations
(Fan & Stevenson, 2018)	The identification, assessment, treatment, and monitoring of supply chain risks, with the aid of the internal implementation of tools, techniques and strategies and of external coordination and collaboration with supply chain members so as to reduce vulnerability and ensure continuity coupled with profitability, leading to competitive advantage
(Baryannis et al., 2019)	A process that encompasses the collaborative and coordinated efforts of all parties involved in a SC to reduce vulnerability and increase robustness and resilience of the supply chain, ensuring profitability and continuity

Table B. 3 - Classifications concerning SCR types. Source: João Azinhais

Authors	Risk Types
(Jüttner et al., 2003; Shekarian & Mellat Parast, 2021)	- Environmental risk - Network-related risk - Organizational risk
(Christopher & Peck, 2004)	- External to the network: environmental risk - External to the firm but internal to the SC network: demand and supply risks - Internal to the firm: process and control risks
(Blos et al., 2009; C. S. Tang, 2006);	- Operational risks: uncertain customer demand, supply and cost - Disruption risks: earthquakes, floods, hurricanes, terrorist attacks, economic crises
(Bogataj & Bogataj, 2007)	- Supply, process (production and distribution), demand, control and environmental risks
(Tang & Tomlin, 2008)	- Supply, process, demand, intellectual property, behavioural and political/ social risks
(Wagner & Bode, 2008)	- Demand side; supply side; regulatory, legal and infrastructure risk and catastrophic risk
(Samvedi et al., 2013)	- Supply, demand, process and environmental risks
(Ho et al., 2015)	- Macro-risks (natural and man-made risks) - Micro-risks (demand, manufacturing, supply and infrastructural risks).
(Ghadir et al., 2022)	- Demand side risks; supply side risks; logistics, political and manufacturing risks

Appendix C – Methodology

C.1 Semi-structured interview questionnaire for SCRI stage

Background Information

1. What are your roles and responsibilities in VW AE?
2. For how long have you been working….
    a. … in the automotive industry?
    b. … in SC management functions?

Specific Questions

1. When and how did you realize that the automotive SC was facing semiconductor shortages?
2. Which of these risks related to the semiconductor crisis induced by the COVID-19 pandemic have you identified in VW AE's SC?
    a. SC disruption
    b. Supply failure
    c. Supplier Delay
    d. Lack of supplier's capacity
    e. Supplier Quality Problem
    f. Supplier Insolvency or bankruptcy
    g. Delay in transporting Supplies
    h. Damage resulting from transport
    i. Incapacity of satisfying car demand within normal lead time
    j. Production Failure
    k. Accident (fire or other)
    l. Natural disaster
    m. Strike
3. Classify the risks identified, considering the impact that each one produced in VW AE´s SC, on a scale of 1 to 5, being 1 the least impact and 5 the highest impact (only asked to the SC manager).
4. What are the techniques/methods used by VW AE to identify risks that could impact the automotive SC?
5. Who is internally responsible for the identification of these risks?
6. How often is done a risk identification process?
7. Which kind of information is used in this process?
8. Which stakeholders are usually involved in this process?
9. How important is it for VW AE to be able to identify SC risks?

C.2 Semi-structured interview questionnaire for SCRT stage

Background Information

3. What are your roles and responsibilities in VW AE?
4. For how long have you been working….
    a. … in the automotive industry?
    b. … in SC/logistic management functions?

Specific Questions

1. What were the risk mitigation measures implemented by the VW group and VW AE to deal with the semiconductor crisis, and what are the main benefits that each of them has brought?
2. Which of these mitigation measures do you think VW AE can take and what repercussions would they have?
    a. Increase safety stocks for semiconductors (whether at VW AE or at suppliers/sub-suppliers).
    b. Perform a critical analysis of sub-suppliers in the supply chain and adjust stocks according to criticality.
    c. Investing in multiple sourcing, this is, new 1st tier suppliers, to diminish the risk of production failures that occur after supply failures.
    d. Investing in backup suppliers, which must be activated after a disruption or a crisis.
    e. Have more flexible contracts with sub-suppliers, which allow placing orders above the normal when it is necessary.
    f. Investing in standardization, modularization and the use of common parts, in order to diminish the number of stock keeping units (SKUs), and consequently, reduce SC complexity.
    g. Investing in proactive risk management measures, which allow the assessment of the current status of suppliers/sub-suppliers, taking into account their performance history in material deliveries and the context of market volatility/scarcity, in order to try to estimate the probability of occurrence and impact of possible future disruptions.
3. How do you consider that VW AE´s SC can become more resilient, in order to deal with future disruptions, namely, what role each of the following topics can play?

a. Investing more in prevention and proactive management of problems.
b. Investing in raising SC visibility and getting to know more sub-suppliers (more layers of the SC).
c. Collaborate more and more with suppliers, through increasingly effective communication systems.
d. Make the organization more agile in solving problems, by investing in new technologies, such as Big Data or Artificial Intelligence, namely in managing and interpreting logistic data and market volatility patterns.
e. Investing in innovation, in projects that allow optimizing logistics flows within the VW AE´s SC.

C.3 Stakeholder Engagement Process for SCR monitoring

Firstly, to be effective, the SCR monitoring stage should involve all the relevant stakeholders. In the case of the supply failure risk, the SCM team, composed of several hierarchy levels (SC analysts, SC coordinators and SC manager) and the first-tier suppliers are the main actors that must be involved. Some measures that can be applied to guarantee the effectiveness of the SCR monitoring stage and engagement of these stakeholders are:

- The SC analysts, in the regular meetings that they have with first-tier suppliers, should monitor the supply failure risk, asking the supplier about its level of confidence in delivering the scheduled supplies. As VW AE works in JIT/JIS, it is not only important to confirm the shipping of supplies but also to comply with the time windows defined.
- The SC analysts should give their SC coordinator the relevant information collected in the meeting with the supplier, in order to help the SC coordinator in estimating the occurrence of a supply failure.
- The SC coordinators should collect the information given by the SC analysts and try to estimate the probability of occurrence of the supply failure risk. Then, they should prioritize the risk of supply failures of the different suppliers and report to the SC manager the most important ones, this is, the ones that have a higher probability of occurrence and might produce a higher impact on VW AE´s SC. Besides, SC coordinators should also encourage the SC analysts to deliver the most accurate information possible.
- The SC manager must also be involved in the process, fostering meetings with the SC coordinators to collect the most relevant supply failure risks. Then, the SC manager and SC coordinators must discuss the relevant measures to limit the impacts that the risk can produce. The SC manager should also inform the logistics business unit measure about the impact that the occurrence of the risk might have.
- The logistics business unit manager should organize a meeting with the production business unit manager to assess how the occurrence of the supply failure risks can impact the production failure risk.
- After the measures have been decided by the highest hierarchy levels, the communication must be effective and the SC coordinators must inform their SC analysts about the measures implemented. The SC analysts will monitor the efficacy of the measures in diminishing the probability of occurring a supply failure. If the measures are not producing effects, they must report it to SC coordinators, who should inform the SC manager and, together with him/her, make the needed modifications or even create new measures.

- It is also important that VW AE persuades the first-tier suppliers in applying the SCR monitoring stage in their organizations and with their suppliers (second-tier suppliers), to engage as many stakeholders as possible, in order to obtain a more reliable flow of information.
- It is also critical that VW AE fosters an organizational culture that gives importance to the SCRM process in general and the SCR monitoring stage in particular. In this way, VW AE should invest in training their workers in SCRM, providing them courses with specialists in this area.
- Besides, VW AE can also stimulate the application of SCR monitoring practices through the assignment of productivity awards to workers that implement a SCR monitoring process in their daily work routine, stimulating other workers in applying it also.